

ADVANCED PORTABLE DIFFERENTIAL IMAGE MOTION MONITOR

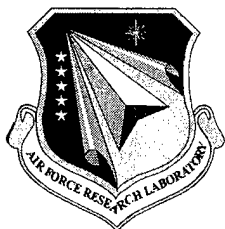
Charles Richey

Mechanical & Composite Engineering
59775 Spring Creek Road
Montrose, CO 81401

April 2000

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.



AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data, does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

If you change your address, wish to be removed from this mailing list, or your organization no longer employs the addressee, please notify AFRL/DEBA, 3550 Aberdeen Ave SE, Kirtland AFB, NM 87117-5776.

Do not return copies of this report unless contractual obligations or notice on a specific document requires its return.

This report has been approved for publication.



FRANK D. EATON
Project Manager

FOR THE COMMANDER



KIMBERLEY A. McCRAE
Chief, Airborne Laser Technology Branch



R. EARL GOOD, SES
Director, Directed Energy

REPORT DOCUMENTATION PAGE*Form Approved*
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) 28-04-2000		2. REPORT TYPE Final		3. DATES COVERED (From - To) 5/99-4/00	
4. TITLE AND SUBTITLE ADVANCED PORTABLE DIFFERENTIAL IMAGE MOTION MONITOR				5a. CONTRACT NUMBER F29601-99-C-0046	
				5b. GRANT NUMBER NA	
				5c. PROGRAM ELEMENT NUMBER 65502F	
6. AUTHOR(S) Charles Richey				5d. PROJECT NUMBER 3005	
				5e. TASK NUMBER DO	
				5f. WORK UNIT NUMBER BL	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Mechanical & Composite Engineering 59775 Spring Creek Road Montrose, CO 81401				8. PERFORMING ORGANIZATION REPORT NUMBER NA	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Directed Energy Directorate 3550 Aberdeen Ave SE Air Force Materiel Command Kirtland AFB, NM 87117-5776				10. SPONSOR/MONITOR'S ACRONYM(S) NA	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-DE-TR-2000-1023	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution is Unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Atmospheric turbulence severely limits the resolution attainable with most astronomical imaging systems, yet quantitative characterization of turbulence conditions remains a difficult and expensive proposition. The goal of this project was to demonstrate that a dual aperture instrument could be constructed, primarily from commercial off-the-shelf (COTS) components, to serve as an inexpensive, easy to operate, seeing monitor. To this end, Mechanical & Composite Engineering (MCE) designed, integrated, tested, and delivered a dual aperture Differential Image Motion Measurement (DIMM) system. The system features high frame rate CCD cameras, a portable computer controlled tracking mount, and easy to use software running on a personal computer under the Windows NT operating system. Among the unique features of this system are a variable spacing between the sub-apertures, and independent frame rate and exposure time control of the CCD cameras. Standard output includes the transverse coherence length and the variance of the angle of arrival for each sub-aperture.					
15. SUBJECT TERMS refractive index structure parameter, transverse coherence length, optical turbulence					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 48	19a. NAME OF RESPONSIBLE PERSON Frank D. Eaton
a. REPORT Uncl.	b. ABSTRACT Uncl.	c. THIS PAGE Uncl.			19b. TELEPHONE NUMBER (include area code) (505) 853-1091

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page left intentionally blank

Table of Contents

1. Introduction	1
2. Theory	1
3. Portability	2
4. Sensor Selection	3
5. Calibration	5
6. Daytime Operation	7
7. Operability and Maintainability	7
8. Results	9
9. Summary	10
10. References	11
Appendix:	
User's Manual for the MCE DIMM system	13
DIMM Software User's Manual	23
DIMM 2-Axis Mount Mechanics	28

This page left intentionally blank

1. Introduction

The goal of this Small Business Innovative Research (SBIR) Phase I work effort was to develop a next generation Differential Image Motion Monitor (DIMM) that consists almost entirely of Commercial-off-the-Shelf (COTS) components, while mitigating the major deficiencies of existing systems. Unlike many Phase I projects, we sought to deliver more than just a feasibility study/technical report. Our goal was to deliver a functioning system. We accomplished that objective with the system shown in Figure 1.

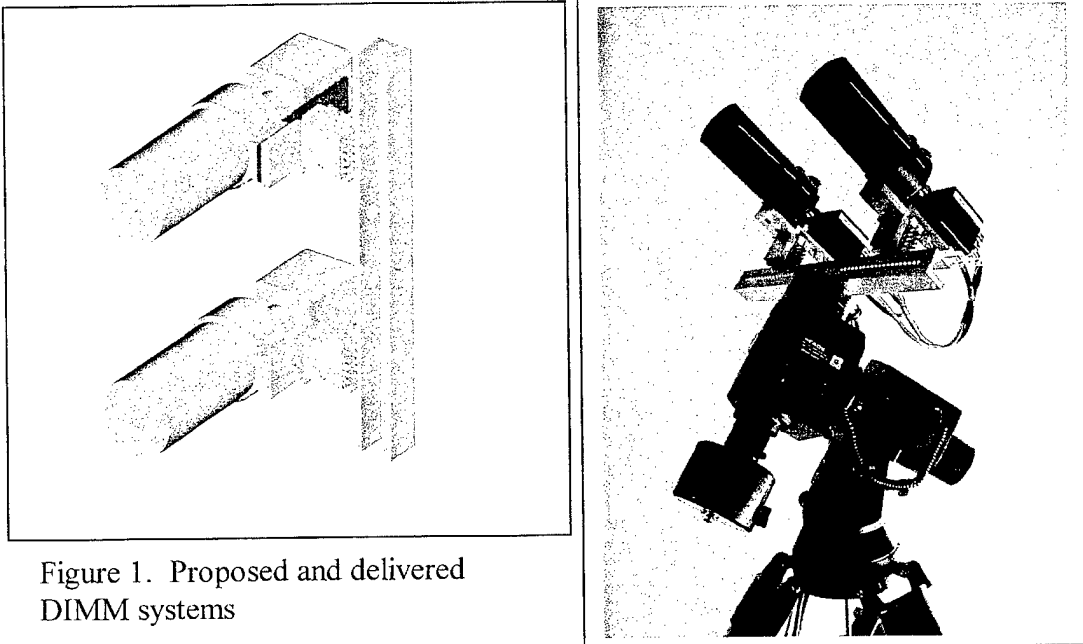


Figure 1. Proposed and delivered DIMM systems

This report is organized to address each of the major technical objectives outlined in our Phase I proposal. We begin with a brief description of the theory behind our measurement technique, followed by a discussion of specific technical objectives. An abbreviated version of the Operations Manual for the prototype DIMM system delivered under Phase I is included as an Appendix.

2. Theory

The fundamental premise of our DIMM instrument is based on classical turbulence theory. The concept is that as light propagates through the atmosphere it encounters regions of slightly different density, and hence refractive index. These regions are commonly referred to as turbulent eddies. For starlight, the refraction caused by these eddies results in distortion of the initial plane wavefront. For small aperture receivers and short exposures, these distortions are manifested primarily as first order phase shifts, or wavefront tilt. In a practical sense, variations in wavefront tilt are equivalent to variations in the apparent angle of arrival, which is recorded as image motion by our

DIMM system. For “weak, nonsaturated” turbulence, the amount of image motion relates directly to the strength or intensity of the turbulence. In the early 1960’s Fried introduced the concept of the transverse coherence length, which ultimately became known as Fried’s seeing parameter, or r_0 . As derived by Fried¹:

$$r_0 = [(0.3584 \lambda^2)/(D^{1/3})(\alpha^2)]^{3/5} \quad (1)$$

Where: λ = wavelength of the light

D = aperture diameter of the receiver

α^2 = variance of the angle of arrival

Equation (1) has been used extensively to determine r_0 from single aperture image motion measurements. As an improvement to the single image motion measurement technique, Stock and Keller² suggested the use of differential measurements. By employing dual apertures and analyzing only the relative motion between the two images, common sources of error, such as telescope tracking and vibration effects, can be eliminated. Our DIMM system uses an expression for r_0 based on differential image motion derived by Roddier³

$$r_0 = \{[\lambda^2/(\alpha_{\text{diff}}^2)] (0.716 D^{-1/3} - .484 u^{-1/3})\}^{3/5} \quad (2)$$

Where: α_{diff}^2 = differential variance of the angle of arrival

u = center to center separation distance between dual apertures

The separation between subapertures and the exposure time employed by the detection system are important considerations for differential image motion measurements^{4,5}. As presented in the discussion that follows, our ability to vary these parameters by integrating COTS components into a readily portable system forms the basis for the innovative features of our project.

3. Portability

Our Phase I objective was to achieve a modular, lightweight, portable prototype DIMM system with adjustable aperture separation by using two small-aperture COTS telescopes and a COTS tracking mount.

For DIMM measurements, it is desirable to have a variable aperture separation, perhaps as much as a meter or more, yet the nature of telescope systems is such that as the aperture increases, the overall size, weight, and expense of the optics and tracking system increase almost exponentially. MCE has demonstrated the feasibility of integrating multiple small-aperture telescopes on a single tracking mount to dramatically decrease the required size and weight of the overall optical system. This innovative arrangement meets the conceptual design criteria specified in SBIR Topic AF99-015.

The prototype DIMM system delivered to the Government under this Phase I SBIR contract consists of three major components.

3.1 Tracking mount with supporting tripod: This component consists of a commercially available Meade LXD 750 German equatorial mount with computer-controlled Right Ascension and Declination motorized drive mechanisms. The computer control is provided by the Meade #1697 Computer Drive System and the tracking and pointing capability automated by Meade's Magellan II Computer-Corrector System, model #2018. This mount is also controllable via the DIMM system control computer (described below). This feature has been utilized to establish a closed loop feedback from the MCE system control software to provide auto-tracking of stellar images using the DIMM digital camera data. The tracking mount component is designed to be easily disassembled (into three parts: tripod, mount head, counterweight), transported and re-assembled by one person with no special tools.

3.2 Telescope/camera sub-assembly: This component consists of two Meade ETX-90 telescopes (90 mm aperture), two Dalsa CA-D6 digital CCD cameras (described in the "Sensor Selection" below), and a fabricated support bar / alignment fixture (described fully in the Appendix). Each telescope-camera pair is mounted rigidly to the support bar via an adjustable, preloaded Cardo hinge that affords boresight alignment of the two pairs. This sub-assembly remains intact and is transported as a single unit. This unit mounts rigidly to the tracking mount via two bolts through the support bar. The support bar has a series of holes along its length to allow variable separations between the telescopes via the Cardo hinge attachment interface.

3.3 Data acquisition and system control computer: The control computer consists of a commercially available Intel motherboard with standard components and two Imaging Technologies Inc. (ITI) PC-DIG frame grabbers. Interconnections between this computer and the rest of the DIMM are discussed in the Appendix (MCE DIMM User's Manual).

The portability of our DIMM was demonstrated during field tests conducted prior to system delivery. The COTS tracking mount is simple to set up and operate, and for short-term tracking sessions it performs satisfactorily after a cursory set up without benefit of the closed loop feedback from the cameras. Limitations on the utility of this mount are discussed in the Appendix. In some of the earlier field tests, an unacceptable amount of flexing between the telescopes and the cameras was encountered due to the variable loading caused by the camera cables as the DIMM tracked stars for extended periods of time. Both of these problems were addressed and corrected prior to system delivery.

4. Sensor Selection

Our Phase I objective was to identify, procure, and integrate two commercially available CCD sensors and frame grabbers into the new DIMM system.

Two Dalsa CA-D6 CCD cameras and two Imaging Technologies PC-DIG frame grabbers were successfully identified, procured and integrated into the overall DIMM system during the Phase I effort. A variety of pre-defined desirable characteristics for these items were outlined in the original Phase I proposal. While a number of camera and frame grabber combinations were studied, there were no combinations that offered a complete off-the-shelf solution that would meet all of the design criteria. The main stumbling block was the availability of a high sensitivity, 12-bit camera that has adequate exposure and synchronizing controls. A list of the main design goals for Phase I includes the following:

- A small sensor array,
- Direct RS-422 or RS-644 digital read-out,
- High signal to noise ratio (12-bits or better),
- Exposure control down to less than two milliseconds,
- Moderately high frame rates,
- Non-interlaced exposure and read-out,
- Square pixels with 100% fill factor,
- Sufficient dynamic range and light sensitivity to observe first magnitude stars with 90 mm diameter apertures and 1 ms exposures,
- Appropriate mechanisms for precisely synchronizing multiple cameras, such that the multiple sensors expose simultaneously,
- Minimal sensor read-out artifacts, such as frame transfer smear.

The chosen cameras and frame grabbers were found to meet and exceed almost all of the initial specifications outlined for the system. The cameras consist of a 256x256 frame transfer CCD capable of framing at rates of up to 955 full frames per second with negligible read-out artifacts. The very high frame rate provides the ability to easily capture frequency domain characteristics, such as the Greenwood frequency and PSDs. Exposure control is independent of the frame rate and can be varied from sub-millisecond up to the full frame time. Our Phase I DIMM system provides a combination of hardware and software mechanisms for precisely synchronizing exposures from multiple cameras along with the ability to capture and process the resulting images.

The CCD sensor is comprised of square pixels with 100% fill factor, resulting in zero geometric distortion and an efficient light gathering capability. While the camera has relatively good sensitivity and dynamic range, testing has shown that a first magnitude star requires a minimum integration time of 2 to 5 milliseconds. This falls just short of the desired goal of capturing images with a 1 millisecond integration without the aid of

an intensifier. In Phase II, various alternatives, including image intensification, will be examined to increase the sensitivity of the image capture mechanism.

The camera system as it is currently implemented is based on the RS-644 low voltage differential signaling standard. This format allows the data to be transmitted over long enough distances to allow for a "local" remote operation, where the computer system can be placed up to 100 feet away from the telescope system. The current system is supplied with 10 foot cables, but those can be replaced with longer cables of up to 100 feet without affecting the integrity of the data.

When both cameras are operating at high or maximum frame rate, the required data bandwidth is extremely high. The maximum rate for both cameras can exceed 140 Mbytes per second. The achievable bandwidth through a standard WindowsNT PCI bus is only about 100 Mbytes/second for sustained throughput. MCE has developed a mechanism for information compression that will allow the system to capture the required information at the full bandwidth of the cameras.

5. Calibration

The stated objective for calibration of the MCE DIMM system was to employ a source of known differential image motion as a reference standard.

A successful, though limited, test of this calibration method was performed using an uncharacterized prototype differential image motion generator as the reference source of moving light spots. The device was comprised of two nominally identical 8-element linear LED arrays flashed synchronously in a shuttle-type pattern. The array elements were spaced at 0.15 inch on center (1.05 inches between centers of endmost elements in each array).

This preliminary calibration test was performed using the complete DIMM system, with each telescope centered on a separate source array. The reference source was located approximately 120 ft from the telescopes (for a subtended angle of roughly 150 arc-seconds), predicted to result in a maximum image translation (source array image length) of approximately 100 pixels on each camera's CCD. The source array length was later normalized to an average array image length in order to allow accurate comparison of light motion between the source and image.

The predicted image length of the source array was based on a plate scale derived from star drift measurements. Using combined data from both cameras, a scale of 0.648 ± 0.001 pixels per arc-second was calculated. The field of view of each camera (256 x 256 pixels) was therefore 395 arc-seconds.

Analysis was performed on five 250-frame data runs that included variations in frame rate, exposure time, and rotational relationship between source array and camera. The results are presented in the following table:

Table 1. Results of MCE DIMM System Calibration

	ref. source	data run #1		data run #2		data run #3		data run #4		data run #5	
frame rate ¹		30 fps		100 fps		100 fps		30 fps		10 fps	
exposure time ²		1 ms		1 ms		1 ms		5 ms		5 ms	
source flash rate ³		4.0/sec		4.0/sec		4.0/sec		4.0/sec		3.2/sec	
source cycles ⁴		2.4		0.7		0.7		2.4		5.7	
		cam 0	cam 1	cam 0	cam 1	cam 0	cam 1	cam 0	cam 1	cam 0	cam 1
source rotation ⁵		+1°	-1°	+1°	-1°	-49°	+45°	-47°	+45°	-47°	+45°
source length ⁶	105	102	105	101	105	102	107	106	106	106	106
variance ⁷	1030	1086	1114	927	965	917	972	1115	1110	1105	1092
std deviation ⁷	32.1	33.0	33.4	30.5	31.1	30.3	31.2	33.4	33.3	33.2	33.0
error, pixels ⁸		0.9	1.3	1.6	1.0	1.8	0.9	1.3	1.2	1.1	0.9
error, % of std dev		3%	4%	5%	3%	6%	3%	4%	4%	4%	3%

¹ frames per second recorded, set

² time of centroid averaging for each recorded frame, set

³ changes per second in lighting of the elements of each source array, observed

⁴ number of complete source array "shuttle" cycles recorded during data run, observed

⁵ rotational angle of the array relative to "horizontal" on the camera CCD, observed

⁶ difference in the image centroid locations (in pixels) between terminal elements of an array, observed

⁷ calculated using all data points in data runs that included 2 or more full source cycles, and using extrapolated data to complete one full cycle for data runs #2 and #3

⁸ difference between standard deviations of measurement and of reference source

Because r_0 is based on angle of arrival variance calculated from a set of image centroid measurements, it is useful to measure a source with a known variance. The "standard" variance generated by the reference source array was calculated from the pattern of the LED flashing cycle and the known array dimensions normalized to 105-pixels (the average array image length). With precise measurement of the distance between reference source and camera, a precise prediction of array image length could be made, allowing a completely independent calculation of the reference variance.

Analysis of the results was very encouraging. No apparent differences resulted from changes in frame rate, exposure time, or rotational angle of the reference source. The errors observed were small, averaging 4%. The performance of the MCE DIMM system in this calibration test compares very well with the performance of "prior art" in the field of differential image motion measurement, indicating a significant potential error reduction.

6. Daytime Operation

Our Phase I objective was to extend the data acquisition operability of the next generation DIMM system to first magnitude stars during the daytime. If necessary, we will add intensifiers, variable filters, etc. during Phase II.

Our past experience suggests that the intensity of first magnitude stars is sufficient to make them visible to a scientific quality sensor during the daytime. The key is to distinguish the stellar signal from the background radiation. In previous work, we have utilized a gated, microchannel plate intensifier to aid in this discrimination, but we believe that simply using a 10 or 12 bit sensor (1024 or 4096 gray levels), as opposed to the 8 bit (256 gray levels) intensified sensor previously employed, will make daytime stellar data acquisition possible. The first camera that we procured featured 10 bits of dynamic range, but we ultimately had to return it to the manufacturer when we discovered that it could not be synchronized on a frame-by-frame basis. As a consequence, we were forced to postpone this part of the investigation in favor of establishing the more fundamental capability of using two independent telescope/camera systems for the DIMM technique. This capability has now been demonstrated and we are in dialogue with camera manufacturers to obtain usable 12 bit cameras for the Phase II DIMM.

Although we were unable to achieve this Phase I objective, the quality of images obtained with the present prototype DIMM using the 8 bit cameras encourages us to expect that favorable daytime measurements can be obtained with suitable 12 bit cameras.

7. Operability and Maintainability

The objective for the qualities of operability and maintainability was to field a user-friendly and functional DIMM system.

The delivered system easily meets this objective. Each system component is modular, of good quality, and is well suited to this application, providing ease of use and durability to the assembled MCE DIMM system. In the event of a component failure, the modularity allows simple and rapid replacement.

The MCE DIMM system can be readily disassembled into easily handled subunits. Reassembly is likewise very simple and can be accomplished by one person in only a few minutes, with little familiarization required. With only normal care in handling of the optical subsystem, we found that repeated assembly/disassembly cycles had no adverse effect on telescope collimation or co-alignment. The optical subassembly is sufficiently compact and lightweight to remain intact for transport or storage.

To the user of any DIMM system, a very important factor in ease of use is the system control and data acquisition/analysis computer and its software. The MCE DIMM uses an interface and operating system that is expected to be familiar to any user: the generic personal computer and the Windows NT[®] operating system.

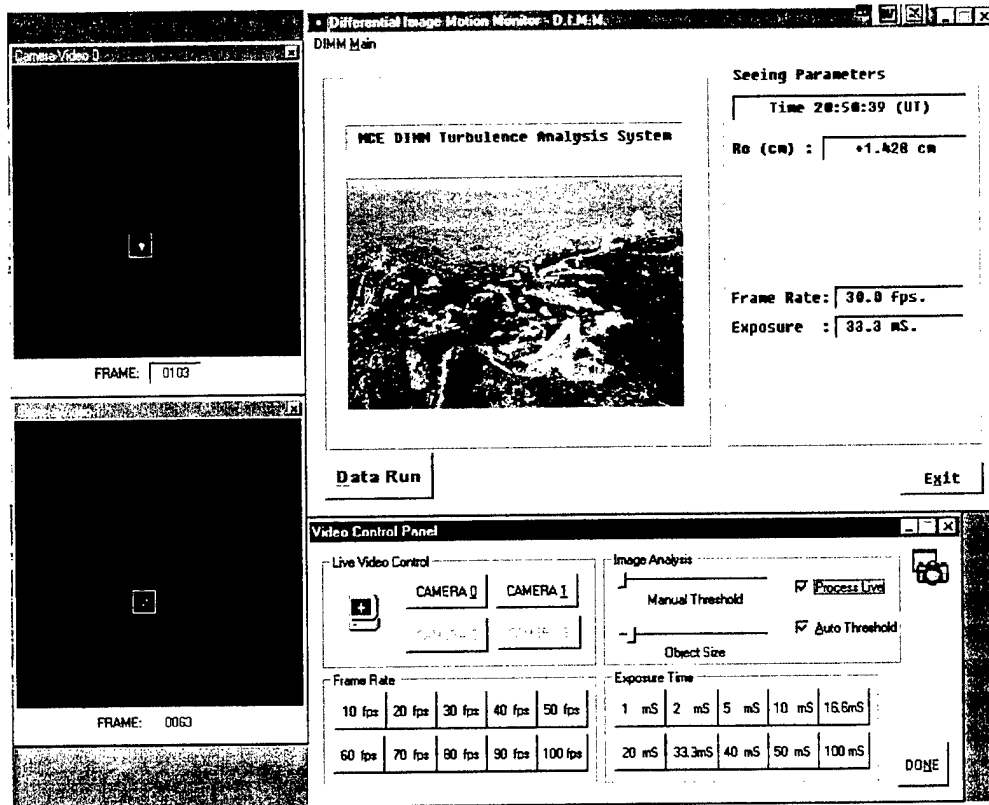


Figure 2. Graphical user interface showing method of choosing frame rate, exposure time, threshold level, etc., for a two-camera system.

The MCE DIMM software was designed to be intuitive and simple to use. Upon starting the DIMM program, the main program window is displayed, and all program functions can be accessed in a manner that is common to familiar Windows[®]-based programs. Subwindows display live output from both cameras, either unprocessed or enhanced (binarized). Details of the program usage and functions can be found in the User's Manual (Appendix).

The program version released with the delivered prototype DIMM system was not, of course, a fully mature product and not all planned functions were implemented. An improvement in the file structure to provide logical association of related data files with minimal user intervention is needed. Processed data needs to be displayed in real time in graphical form and implementation of more precise data handling routines are still needed, but all essential characteristics of the measurement technique have been successfully demonstrated with the prototype DIMM.

Updating the MCE software on the DIMM when additional features are implemented is a user-friendly process that merely requires replacing one executable file with another. Updated versions can be easily provided to the user electronically.

8. Results

Our Phase I goal was to demonstrate the feasibility of the independent-telescope DIMM concept by using the instrument to acquire r_0 data on a stellar source.

The proof-of-concept prototype DIMM which was built and delivered to the Government under this contract demonstrated all essential features and functions required to obtain r_0 data from differential image motion (as well as from single image motion). The following tables list the various sets of data obtained with the DIMM hardware configuration in its delivered form -- although the system software was still being debugged.

Date	file ID	Source	frm rate fps	exp time ms	Cam 0 r_0 cm	Cam 1 r_0 cm	Diff r_0 cm
2/12/00	212a	Sirius	30	2	2.8	2.0	2.1
2/12/00	212b	Sirius	30	2	3.6	2.1	2.2
2/12/00	212c	Sirius	30	5	3.4	3.4	4.8
2/14/00	214a2	Sirius	30	2	3.7	4.1	3.8
2/14/00	214b5	Sirius	30	5	3.9	3.7	4.7
2/14/00	214c5	Sirius	30	5	1.8	1.8	4.6
2/14/00	214d2	Sirius	30	2	2.2	3.4	2.2
2/14/00	214e5	Sirius	30	5	4.7	4.7	4.5
2/15/00	215a	Sirius	30	10	4.2	4.2	6.1
2/15/00	215b	Sirius	30	5	4.2	4.0	5.3
2/15/00	215c	Sirius	30	10	6.6	5.7	6.8

Frame-by-frame images were recorded while tracking Sirius and these sets of images were subsequently used to calculate the r_0 values of the table. This stellar data was taken under varying conditions -- including purposeful introduction of extraneous vibrations -- so that the data of the above table should be interpreted as an indication that the DIMM functions properly and not, necessarily, as a true indication of atmospheric turbulence conditions. Although not listed in the above table, data sets were also obtained with the DIMM observing Capella with 5ms exposures.

Table 3. Non-Tracking Results					
Date	file ID	Source	frm rate fps	exp time ms	Purpose of Data Set
2/12/00	212d	Sirius	20	10 ?	star drift trail calibration
2/12/00	212e	Sirius	20	10 ?	star drift trail calibration
2/15/00	212D	Sirius	20	16 2/3	star drift trail calibration
2/15/00	212R	Sirius	20	16 2/3	star drift trail calibration
2/15/00	1D	LEDs	30	1	variance calculation check
2/15/00	1E	LEDs	100	1	variance calculation check
2/15/00	1F	LEDs	100	1	variance calculation check
2/15/00	5F	LEDs	30	5	variance calculation check
2/15/00	5G	LEDs	10	5	variance calculation check

The data represented by the Star Drift Trail and LED entries of Table 3 has been utilized and discussed in the "Calibration" section above. All of these data sets contained 250 frames.

9. Summary

Phase I of this SBIR development has resulted in the completion and delivery of a functional COTS-based advanced portable DIMM system. The MCE team is very proud of this accomplishment. This state-of-the-art DIMM system was designed, manufactured, tested, and delivered on time and within budget. Phase II of this SBIR contract will allow MCE to enhance the product and add additional features to improve the measurement capability of the system, its flexibility and its ease of use. By the end of Phase II, MCE will be well prepared to proceed with the marketing and commercialization of the product.

As described in this report, MCE successfully achieved the majority of objectives that were set forth in the Phase I proposal. Our primary goal was to deliver a functional system at the end of Phase I. While many SBIR Phase I projects result in nothing more than a report, MCE delivered a working product in the short time span afforded by the Phase I contract guidelines. Other significant goals and accomplishments centered around the areas of portability, sensor capabilities, calibration, daytime operation, and overall operation and maintainability. With the exception of daytime operation, each of the project goals were met or exceeded.

The difficulty with daytime operation is a straight forward signal to noise ratio issue. Because of synchronization problems encountered with the first cameras selected, we were forced to defer procurement of high-sensitivity 12-bit cameras until Phase II. In the interim, we had to compromise by selecting a high quality 8 bit camera for the prototype system. For Phase II, we have identified a promising new 12-bit camera (just released in

January 2000) that will be considered as a candidate for meeting the daytime operation requirement.

The delivered Phase I DIMM system represents a first stage prototype system. While the system is currently functional, many enhancements are envisioned for Phase II. These enhancements, outlined in the Phase II proposal, will result in a highly advanced, modular, commercially viable DIMM product suitable for both research and atmospheric turbulence characterization.

10. References

1. D. L. Fried, "Differential angle of arrival: Theory, evaluation, and measurement feasibility," *Radio Science*, 10, (1), pp. 71-76, (1975).
2. J. Stock and G. Keller, "Astronomical Seeing", *Stars and Stellar Systems*, Vol. 1, - *Telescopes*, pp. 138-153, (1960).
3. F. Roddier, "The Effects of Atmospheric Turbulence in Optical Astronomy", *Progress in Optics*, edited by E. Wolfe, 19, pp. 283-377, (1981).
4. David B. Soules, "Vertical Path Atmospheric Turbulence: Temporal Spectra and Differential Image Motion Measurements", Doctoral dissertation, Colorado State University, Spring 1992.
5. David B. Soules, James J. Drexler, Bret F. Draayer, Frank D. Eaton, and John R. Hines, "Exposure-Time Effects on Differential r_0 Measurements", *Publications of the Astronomical Society of the Pacific*, Vol. 108, Number 727, pp. 817-827, September 1996.

Appendix

Selected Sections from **User's Manual for the MCE DIMM System**

MCE
Mechanical and Composite Engineering

February, 2000

General Information

This manual was prepared as part of SBIR Topic AF99-015, Advanced Portable Differential Image Motion Monitor (DIMM), Phase I.

The manual comprises four sections:

- Setup and Operation of the DIMM System
- DIMM Software User's Manual (details of the MCE system software)
- DIMM 2-Axis Mount Mechanics (details of the MCE-built system hardware)
- OEM Instruction Manuals (details of the for the commercially-available components of the system).

Instructions in this manual assume setup in the northern hemisphere, but may be readily adapted to the southern hemisphere.

References (included in this manual)

Meade® ED Apochromatic Refractors Instruction Manual, Meade Instruments Corporation, 1992
Meade® #1697 Computer Drive System Instruction Manual, Meade Instruments Corporation, 1998
ETX Astro Telescope/ETX Spotting Scope Instruction Manual, Meade Instruments Corporation, 1998
Motion Vision® CA-D6-xxxxW High-Speed Area Scan Cameras Camera Users Manual, DALSA Incorporated, 1998

Setup and Operation of the MCE DIMM System

System Setup

Assembly of Mount and Telescopes

The Meade® ED Apochromatic Refractors Instruction Manual covers assembly and basic operation of the equatorial mount and tripod. It should be referred to during the initial setup. The tripod and mount are relatively heavy. Use safe lifting practices and consider assembling the system in the location where it is to be used.

- Set the tripod with the legs fully splayed. Ensure that the mount's tripod adapter is attached to the tripod head.

NOTE: disassembly and reassembly is facilitated by leaving the adapter permanently attached to the tripod.

The azimuth stud must ultimately be oriented north. The corresponding tripod leg can be used to gauge approximate alignment at this point.

- Ensure that the mount's azimuth adjusting screws are backed off or removed, then lower the mount onto the adapter. With the tripod spreader bar arms held against the tripod legs, run the threaded rod up into the mount (Figure 1) and tighten securely, but not so tight that azimuth adjustment is made difficult.

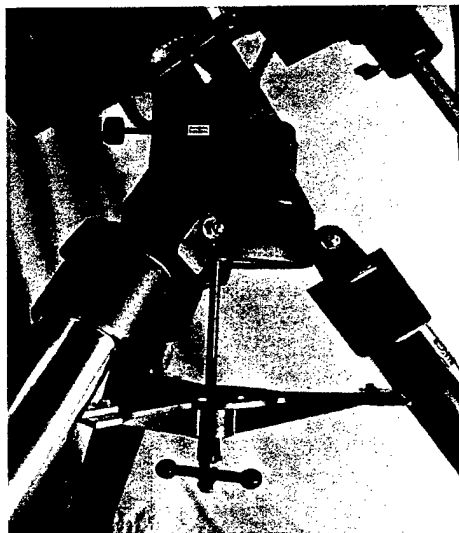


Figure 1. Tripod stabilizer/mount attachment

- Tighten the azimuth adjusting screws so that the azimuth stud is roughly centered in its range (Figure 2).

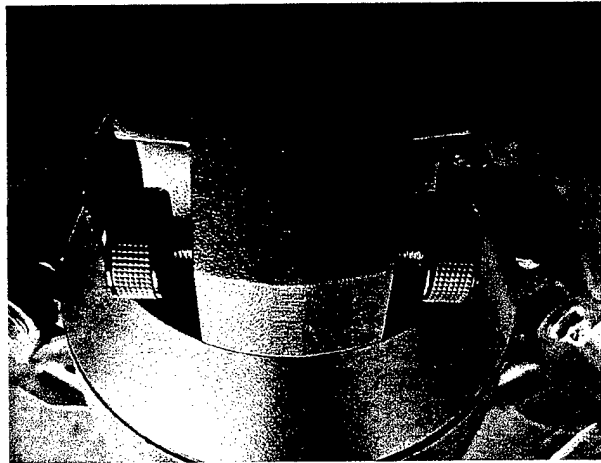


Figure 2. Azimuth adjustment centered

- Ensure that the latitude lock (Figure 3) is loose enough to allow angle adjustment, then use the latitude adjusting screw to set the appropriate angle (the latitude of the site).
- Loosen the Dec and RA locks (Figure 3) and verify free rotation of the shafts. Tighten the locks and verify that no slippage of the axes occurs when a reasonable torque is applied.

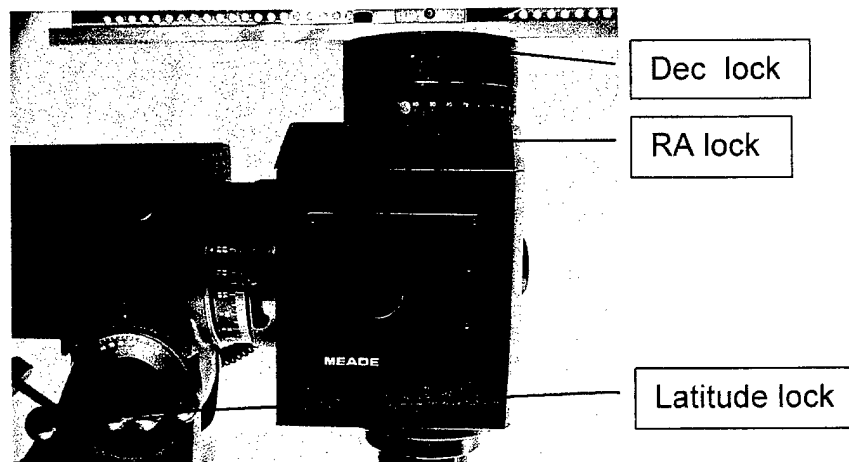


Figure 3. Latitude lock knob and Dec/RA locks

- Ensure that the Dec setting circle appears to indicate correctly and that the setscrew is tight.
- Secure the optical system assembly (Figure 4) to the declination axis mounting plate using two 3/8-16X1" cap screws. The optical system comprises the telescopes, cameras, cables, Cardo hinges, and mounting bar. Refer to the third section of this manual, 2-Axis Mount Mechanics, for details of this assembly.

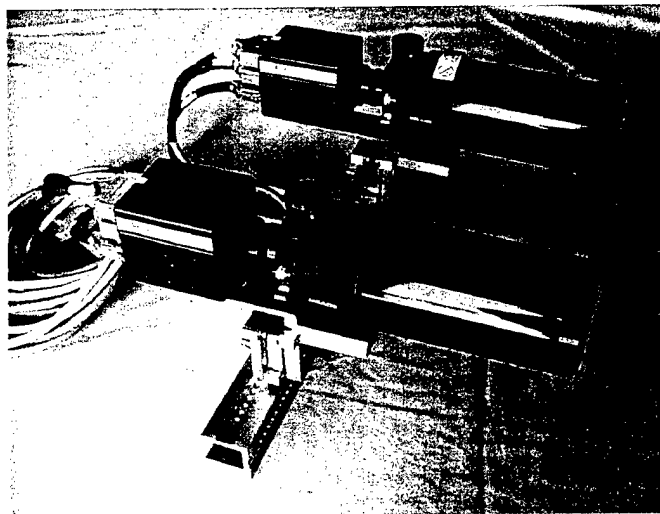


Figure 4. Optical system assembly

- Securely attach the counterweight and position the counterweight shaft to balance the optical assembly (hold the camera cables to simulate an in-use condition).

Collimation of Telescopes

- Install reticle eyepieces in the telescopes. Ensure that the scopes' flip mirrors are set to the eyepiece position, then focus (Figure 5) on a distant terrestrial object. Adjust the pitch and yaw screws on the Cardo hinges (Figure 6) to center the scopes on the same point. Additional yaw adjustment range can be obtained by shifting the scope-to-hinge screws in their holes.

NOTE: For good performance using the methods recommended in this manual, it is not necessary to ensure that the scopes are collimated with the mount's polar axis at 90° declination. However, if the native Meade® CDS alignment routine is used, lack of such collimation will yield poor alignment and poor pointing ability.

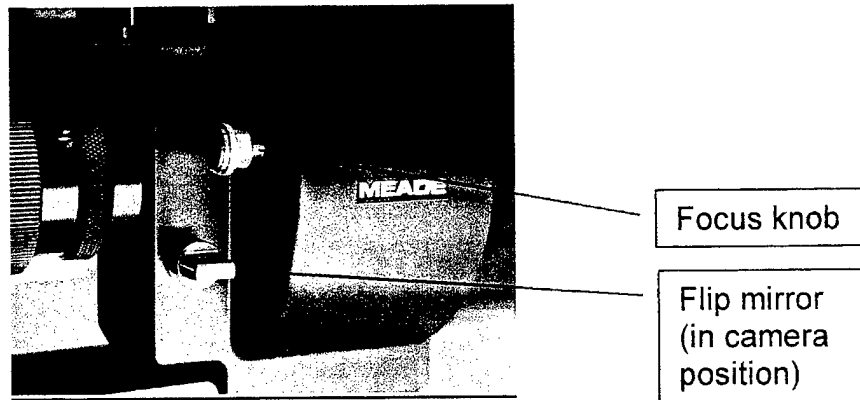


Figure 5. Telescope focus and flip mirror controls

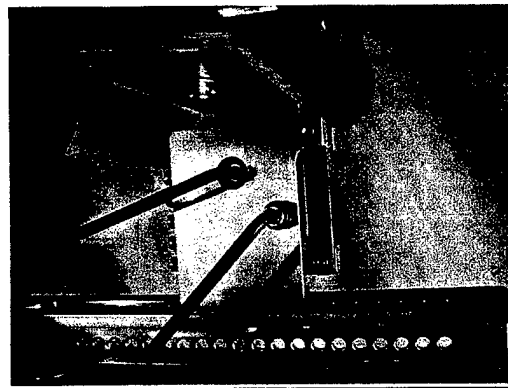


Figure 6. Pitch (upper) and yaw (lower) adjustments on Cardo hinge. Shown with hex wrenches inserted

Tripod Leveling

- If not already done, ensure that the tripod is set on a stable surface and the mount's polar axis is aimed approximately north (so that polar north is within the azimuth adjustment range). Refer to the bubble vial in the mount base and adjust the tripod legs as necessary to achieve level.

PC Setup and Electrical Connections

The PC and camera power supply must be set close enough to the tripod to allow slack in the camera cables through the entire range of the mount's motion.

- Connect the camera power supply cables to any of the connectors (DB9) on the back of the power supply unit.

- Connect the camera data cables to the PC (Figure 7). The system will identify the camera connected to the upper port as Camera 0 and the lower as Camera 1.

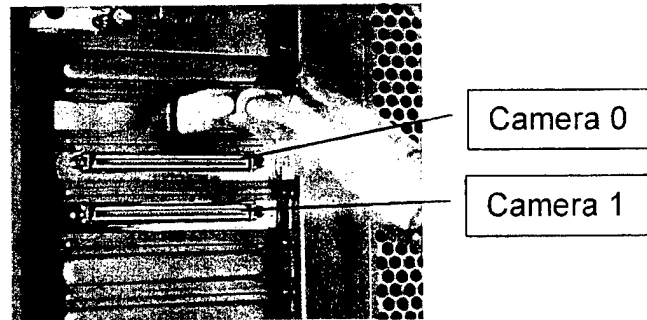


Figure 7. Camera data cable ports on the PC

- Attach the 6-conductor flat telephone-style cable and its 9-pin serial port adapter between the upper serial port on the PC (COM1) and the RS232 jack on the mount's CDS control panel (Figure 8).

NOTE: In the event of replacement of the cable/adapter, care must be taken to preserve the correct pinout.

- Ensure that the power switch on the CDS control panel is off. Connect the CDS power supply cable to the identified jack (18 VDC) on the control panel (Figure 8) and plug the transformer into a line power outlet.
- Connect the hand keypad cable to the Keypad jack on the CDS control panel (Figure 8).
- Ensure that the 8-conductor cable is connected between the RA Motor jack on the mount's RA motor housing and the RA Motor jack on the CDS control panel (Figure 8).

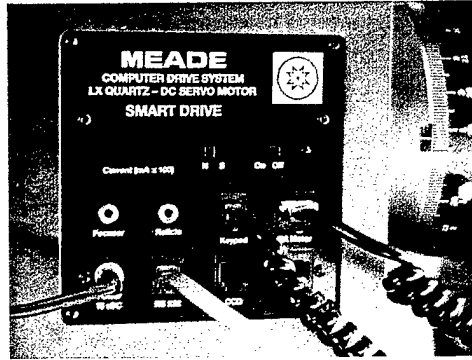


Figure 8. CDS control panel with cables connected

System Operation

CDS Power-up

- Slide the power switch on the CDS control panel to "On" and wait for the CDS self-test to finish. When the CDS is ready for use, the hand keypad will display "TELESCOPE" and "OBJECT LIBRARY". At this point, the RA drive motor will be running and the system tracking.

NOTE: Do not restrain or manually turn the Dec or RA slow-motion knobs when the power is on. To do so can result in destruction of the drive motor/gear assemblies. The direction keys on the hand keypad should be used for slewing when the power is on. Alternatively, it is acceptable to unlock, move, and relock either axis (but note that doing so results in loss of sky synchronization).

Verification of Time and Lat/Long Settings in CDS

NOTE: It is helpful to have an operating GPS (Global Positioning System) receiver to accurately set or verify latitude, longitude, and time.

- If unfamiliar with use of the hand keypad controller, refer to the Meade® #1697 Computer Drive System Instruction Manual.
- On the keypad, select the TELESCOPE menu, then select the SITE menu. Of the four site registers, the active one displays a check mark. With the selector arrow at the active site, hold the enter key to enable editing the site information. Press the enter key to display LAT and LONG values. Ensure the values are correct (edit if necessary).

- Using the mode button, back up the menu tree and then to the display of times. At this point, the enter key toggles between time and date displays. If necessary, hold the enter key to enable editing, then correct the local time (to within a few seconds of accurate, if possible). The GMT offset time is accessed only by enabling editing of the time value then pressing enter. Display the date and edit if necessary (press enter after editing, before exiting via the mode button).

NOTE: If the CDS does not maintain correct time and date with the power switched off, the 3-volt backup battery probably requires replacement. Refer to the CDS Instruction Manual.

Alignment

NOTE: Although it is not recommended, the native CDS align routine can be used to obtain a "casual" alignment. The MCE DIMM software can accommodate the drift that will result. If the native align routine is used, care must be taken to follow exactly the instructions in the Meade® #1697 CDS Instruction Manual. Carelessness in using the align routine can result in the optical system turning "upside down" and ramming the optical system into the mount base or tripod. The only means of aborting the routine or its automatic slew is to switch off the CDS power.

- Remove the lens covers from the telescopes and install a reticle eyepiece.
- Obtain an initial rough alignment by setting the declination to 90° then centering Polaris using only the azimuth and latitude adjustment screws.
- Use the drift method to refine the alignment. When only a barely perceptible north/south drift is observed over a time of about 10 minutes, the azimuth or latitude is adequately set. An adequate alignment can usually be done within half an hour. Following is a brief description of the drift method:

Slew to a star near the intersection of the meridian and the celestial equator. Center this star (the "Guide" slew speed should be used for precise centering) and monitor its apparent north/south drift as the mount tracks. If the star appears to drift southward, the polar axis is aimed too far east and the azimuth setting must be adjusted toward the west. If the drift is northward, the azimuth must be adjusted toward the east. The latitude is set similarly, but using a star near the eastern

horizon (also near the celestial equator). If the star appears to drift southward, the polar axis is aimed too low and the latitude setting must be increased. If the drift is northward, the latitude must be decreased.

Synchronization of CDS to Sky

In order to use the pointing capability of the CDS, the mount must be synchronized to the sky. With accurate times and site coordinates, good polar alignment, and a known point of reference, the CDS is able to point the telescope(s) at any celestial object in its database.

NOTE: Resynchronization is required in the event of slippage (or intentional unlocking) of the Dec/RA axes or interruption of CDS power.

- Slew to a star that is well known (but not near the celestial pole).
- Verify that the Dec and RA locks are tight enough to prevent slipping, then center the star on the reticle using the direction keys and an appropriate slew speed.
- Enter the star's catalog number into the hand keypad (e.g., for Rigel: STAR, 4, 1, ENTER). Then press and hold the enter key until the keypad beeps and displays "Coordinates matched".

PC and Program Start-up

NOTE: If it is desired to verify RS232 communication between the PC and CDS, use Windows® Hyperterminal (com one 9600). Refer to the Meade® #1697 CDS Instruction Manual for the command set. The CDS will accept commands from either the hand keypad or the PC when they are connected concurrently.

- Switch on the power to the PC, monitor, and camera power supply. Start Windows®, then start the DIMM program (double-click the DIMM Executable icon).
- In the DIMM Main menu, open the Video Control Panel.
- Click the Camera0 and Camera1 buttons, then drag the visible Camera Video window to expose the underlying one. Both windows should be black, indicating presence of camera signal.

Obtaining Centered Star Images

- Install 12mm lighted reticle eyepieces in both scopes. Ensure that the scopes' flip mirrors are set to the eyepiece position. Slew to the star of choice and center the star in the eyepiece of one scope. Check the second scope, and adjust its Cardo hinge if necessary to center the star image. Initially it may be helpful to use a 26mm eyepiece to find and roughly center the star, and to check approximate collimation of the scopes.
- After visually centering the star, turn the scope's flip mirror to the camera position. The scope's focus setting must be adjusted because of a difference in length between the eyepiece and camera optical paths (centering can also differ slightly). Experience will allow quick approximate refocusing. The focus must be close to correct in order to see an image on the monitor. If out of focus, the diffused image's light intensity might be below the detection threshold. Adjust the focus while watching the monitor, if possible. The appearance of an open circle usually indicates that focus can be improved. It is useful to monitor with "Process Live" selected to enhance the displayed image.
- Repeat the process on the second scope. Very slight adjustments to the Cardo hinge(s) can be made to exactly center the star images in both Camera Video windows.

Acquiring and Archiving Data

Refer to the following section, DIMM Software User's Manual, for detailed instructions.

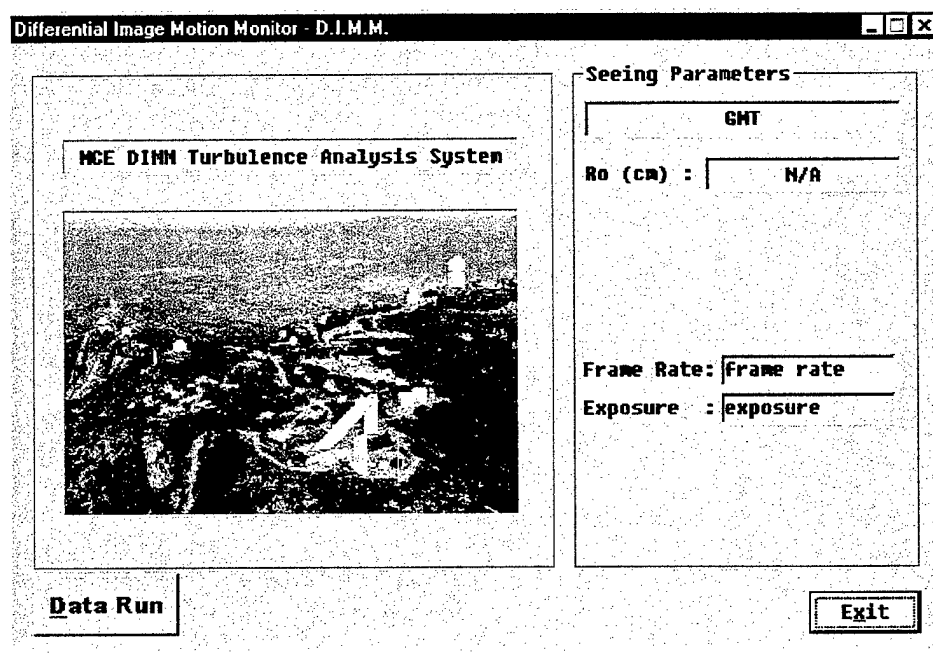
System Shutdown

- Close the DIMM program Camera Video windows, Video Control Panel, and the main DIMM program, then perform the Windows "Shutdown".
- Turn off power to the PC, monitor, camera power supply, and CDS.
- Replace telescope lens covers and eyepiece port covers. Store the eyepieces.
- If necessary to move the system or its components after shutdown, disconnect the cables and dismantle the system to the extent necessary.

DIMM Software Users Manual

1.0 Description

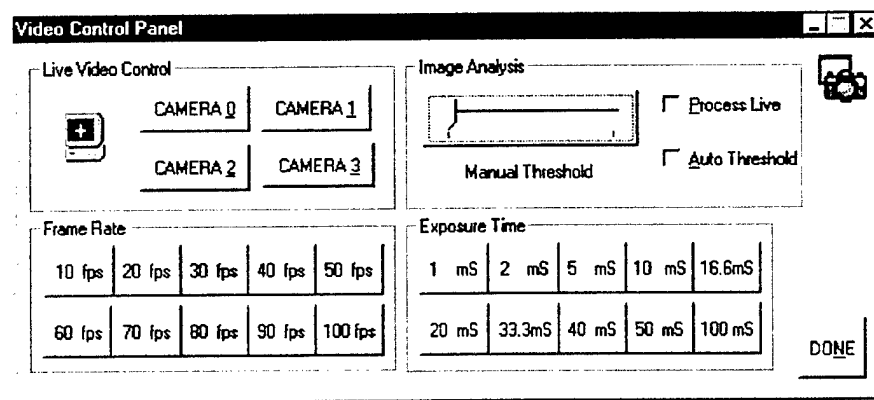
The DIMM system uses a Windows™ GUI based program to perform data acquisition, reduction, and archive. The DIMM is written in C/C++ for Microsoft Visual C++ 6.0™. Third party (Imaging Technologies) drivers and libraries are used to support the PC-DIG frame grabbers. DIMM is made up of several windows which each perform a specific set of functions related to the overall operation of the system. After opening the DIMM executable (DIMM.EXE), you will see the DIMM main window (shown below).



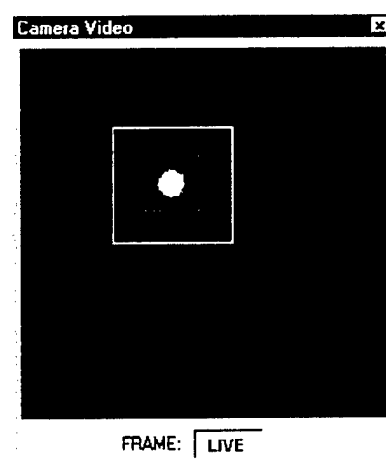
The DIMM main window displays the current system time (GMT), the latest r_0 measurement (centimeters), and the frame rate and exposure time currently being used for data acquisition. Major features are the **Data Run** button, **Exit** button, and the pulldown menu (DIMM Main) in the upper left corner (not shown here). **Data Run** will perform a complete data acquisition and data reduction cycle to produce r_0 . In addition to producing r_0 , a data log file (DIMM.LOG) will be created containing time, two single-image r_0 values, a differential-motion r_0 , and the percentage of frames accepted for the calculations. If desired, centroid files may also be produced after a data run (see Data Reduction section). **Exit** will close all open devices and exit the DIMM system. The main pulldown menu provides access to all other features of the DIMM system.

2.0 Video Control Panel

The first option in the pulldown menu is Video Controls. This displays a window (below) which contains groups of controls for frame rate, exposure time, live video display, and image processing parameters.



The Live Video Control section allows the user to show (or hide) a live video window for each camera (up to a maximum of four). The Frame Rate group allows control of the current frame rate of all cameras from 10 to 100 frames per second. The Exposure Time group allows you to set the integration time of the cameras independent of the frame rate. Any exposure time from 1mS to 100mS is allowed as long as it does not exceed $1/\text{frame rate}$. For example, you may use only exposures from 1mS to 10mS for a frame rate of 100 fps ($1/100\text{fps} = 10\text{mS}$). The last group, Image Analysis, provides access to some of the parameters used to discriminate the star image from background in video image space. The **Process Live** check box, when checked, will locate and identify objects in the field in real time. With a live video window open, you can see the system locate and track objects as a track window appears over any item identified as a candidate object (below).



(Live video window processing a stellar image in live mode)

After **Process Live** is checked, **Auto Threshold** will automatically be checked. This mode causes the DIMM software to determine the brightness level which will be used to binarize the image. Binarization produces two states where all pixels below threshold are considered background, and all others are considered object. The tracking window will appear centered around any item considered to be above threshold. If you wish to experiment with varying the threshold, you may uncheck the **Auto Threshold** check box, and use the threshold slider to select your own level. Pulling the slider to the left reduces the threshold making the system accept dimmer objects. Pulling the slider to the right increases the threshold allowing only bright objects to be recognized. During live processing you can try changing the threshold to see the effect on the image analysis process. During data runs, the system **SHOULD NOT BE IN AUTO THRESHOLD MODE**, as it may affect the resulting amplitude of images on a frame by frame basis.

The next two options on the main menu, **Mount Control** and **System Config**, are not implemented as of release 1.20b. Future use will allow selection of serial parameters and full control over the Meade 1697 CDS. All releases of DIMM do control the CDS to automatically correct tracking error in the mount. This is done through serial commands issued from the PC COM1: serial port. Prior to proper operation, the system must be configured by editing the MOUNT.CFG configuration file. On the second line of this file, you must tell the system which direction to drive the mount in order to make the image (not the mount) go up in the camera field of view. You may enter any one of the following drive directions into line two: NORTH, SOUTH, EAST, WEST. During live processing, the DIMM will automatically issue the proper mount drive commands in order to keep the test object centered in the field of Camera 0. After editing the MOUNT.CFG file, you must exit DIMM and restart the program in order for any changes to take effect. The file may be edited with any ASCII text editor such as NOTEPAD, WORDPAD, or the MSDOS EDIT command. The following is an example of a MOUNT.CFG file telling DIMM that EAST drives the object up in the field of Camera 0:

```
// Indicate on line 2 which direction drives the object UP on camera 0  
EAST
```

(Example of MOUNT.CFG file)

NOTE:

If the MOUNT.CFG file cannot be found by DIMM, a message box will appear warning of this fact. This is not a fatal error as DIMM will default to NORTH if the file cannot be located. This may, however, cause the mount drive to be incorrect and actually drive the image out of the field during live processing.

3.0 Data Reduction

The next main menu option, **Data Reduction**, opens a separate window for data entry (below). This window allows user entry of many of the values which DIMM uses to compute the atmospheric turbulence parameter, r_0 .

The screenshot shows a window titled "Data Reduction" with a close button (X) in the top right corner. Inside the window, there is a section titled "Data Reduction Parameters" containing five input fields:

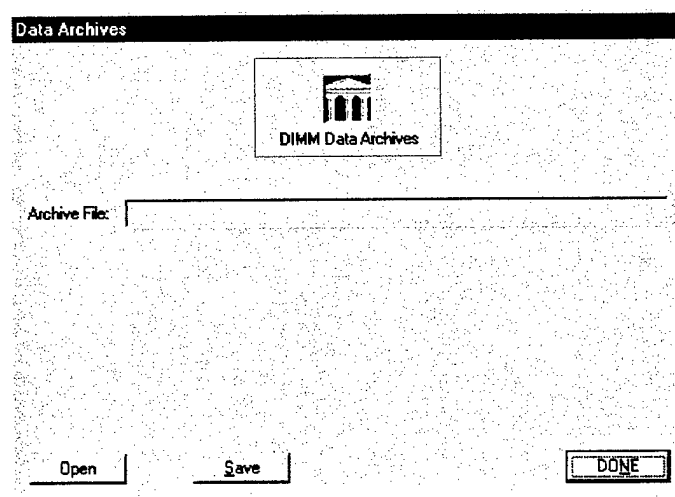
- Aperture Diameter (cm) with the value 9.8
- Aperture Separation (cm) with the value 21.8
- Wavelength (nm) with the value 698
- Focal Length (m) with the value 2.5
- Frame Count (1000 max) with the value 250

Below these fields is a checkbox labeled "Record Centroids" which is checked. At the bottom right of the window are two buttons: "Cancel" and "Apply".

You may change any or all of these values and press **Apply** to dismiss the window and use the new set of values. Pressing **Cancel** will restore the data fields to their default values before dismissing the window. Also on this window is the **Record Centroids** check box. Checking this box will cause the DIMM to record data files for each camera containing the frame number, X centroid, and Y centroid for each frame. The files (CAMERA0.CEN, CAMERA1.CEN, etc.) are in ASCII comma-delimited format, and are produced after every data run. If the files already exist, then new centroid data will be appended to the end of those files.

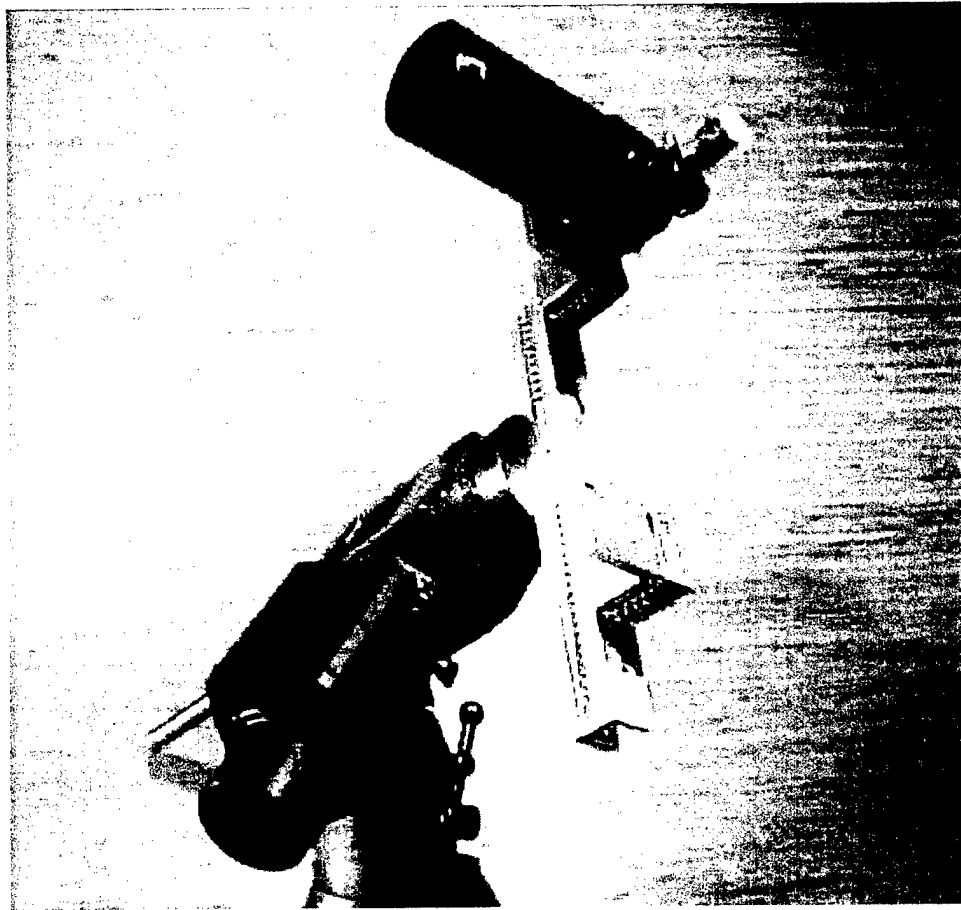
4.0 Archives

The last of the main menu options (with the exception of **Exit**), Archives, allows the user to save and review the raw images acquired by the DIMM system. After a data run, you may open the Archives window (below) to save the data which was just gathered. Pressing the **Save** button will open a standard Windows™ browse dialog and allow you to navigate to the area where you wish to save your images. You may then enter a file name and press **Save** to complete the operation. The file will be written in raw 8-bit pixels, raster ordered then camera ordered format with a 512 byte header. Note, these files can be very large so be sure to have adequate disk space available prior to archiving large data sets. A typical set (250 frames) will require 32MB of disk space.



To open and review a previously saved data set, press the **Open** button. You will then use another dialog box to navigate and locate the file you wish to load. The DIMM default for archives is a *.DAR* extension. Once you have located the file, pressing **Open** on the dialog will read in the archive file from disk. Once loaded, the data will be replayed in real-time on the live video windows. Pressing **DONE** on the archive window will dismiss the window and return the video windows to viewing the live camera video.

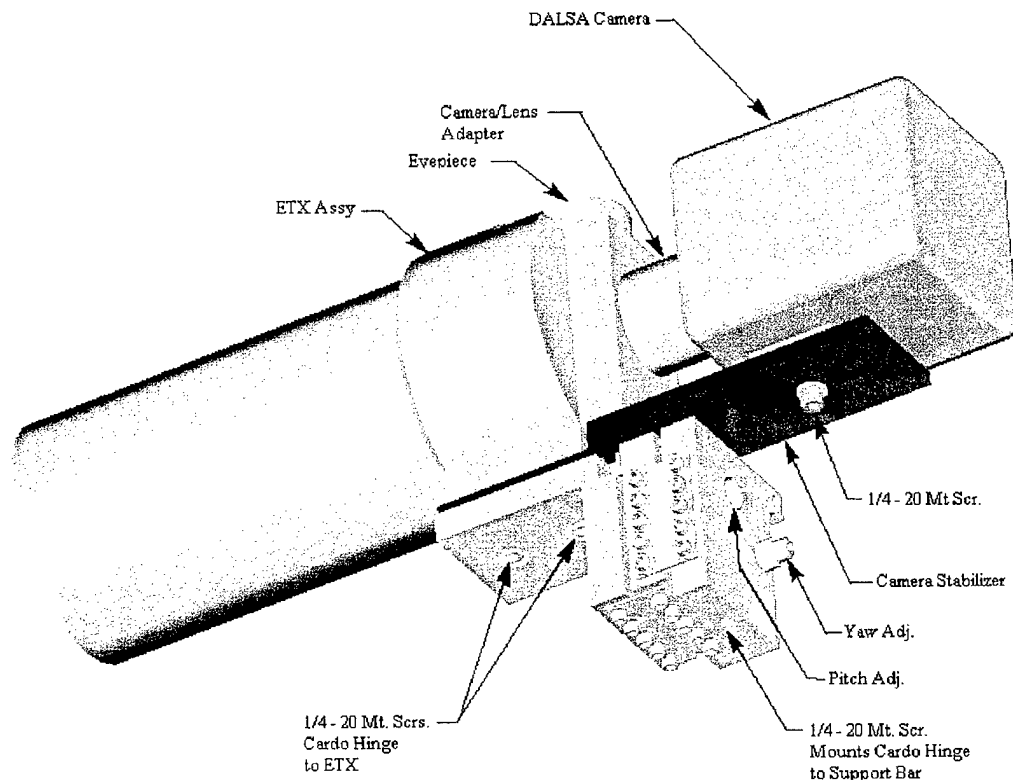
DIMM 2-AXIS MOUNT MECHANICS



90mm ETX Optics Mounted on a LTX 750 Meade Tracking Mount

The Support Bar and two Cardo Hinges are shown.

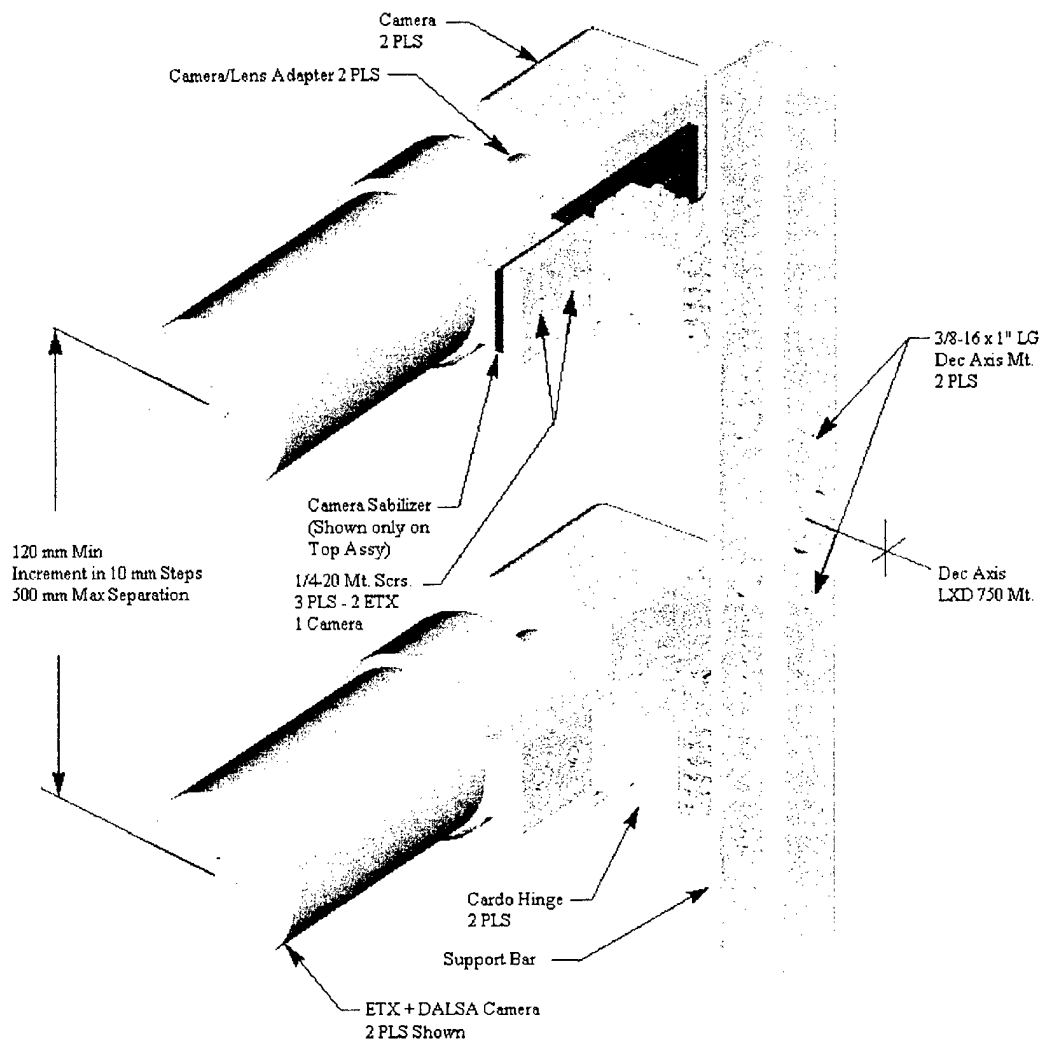
- The Combination of the Support Bar and the Cardo Hinges permits the mounting of multiple optics systems at preset spacing and all collimated to a common view axis.
- *The Cardo Hinges work by flexure and have no mechanical freeplay.* The adjusting screws are preloaded by stiff belleville washer/springs. The hinges, as designed, will withstand one to several hundred in-lb of torque, depending upon the number of bellevilles installed, before upsetting from their normal limits.
- The Cardo Hinges have very definite resonance points, as they are a spring coupled to a mass. *However, the spring-mass system will not resonate at the spring/mass frequency until "upset" off of the stops* – in this condition extraordinary forces are involved (very heavy winds, someone accidentally leaning against the optics, etc.) and the system is temporarily inoperable. After the forces are removed, the system will return to original alignment (if not damaged) and *act as a rigid body*. Think of the hinges as an engine valve and spring – it is not a coupled spring/mass until unseated and will return to its original alignment at closure.



ETX Assembly attached to the Cardo Hinge

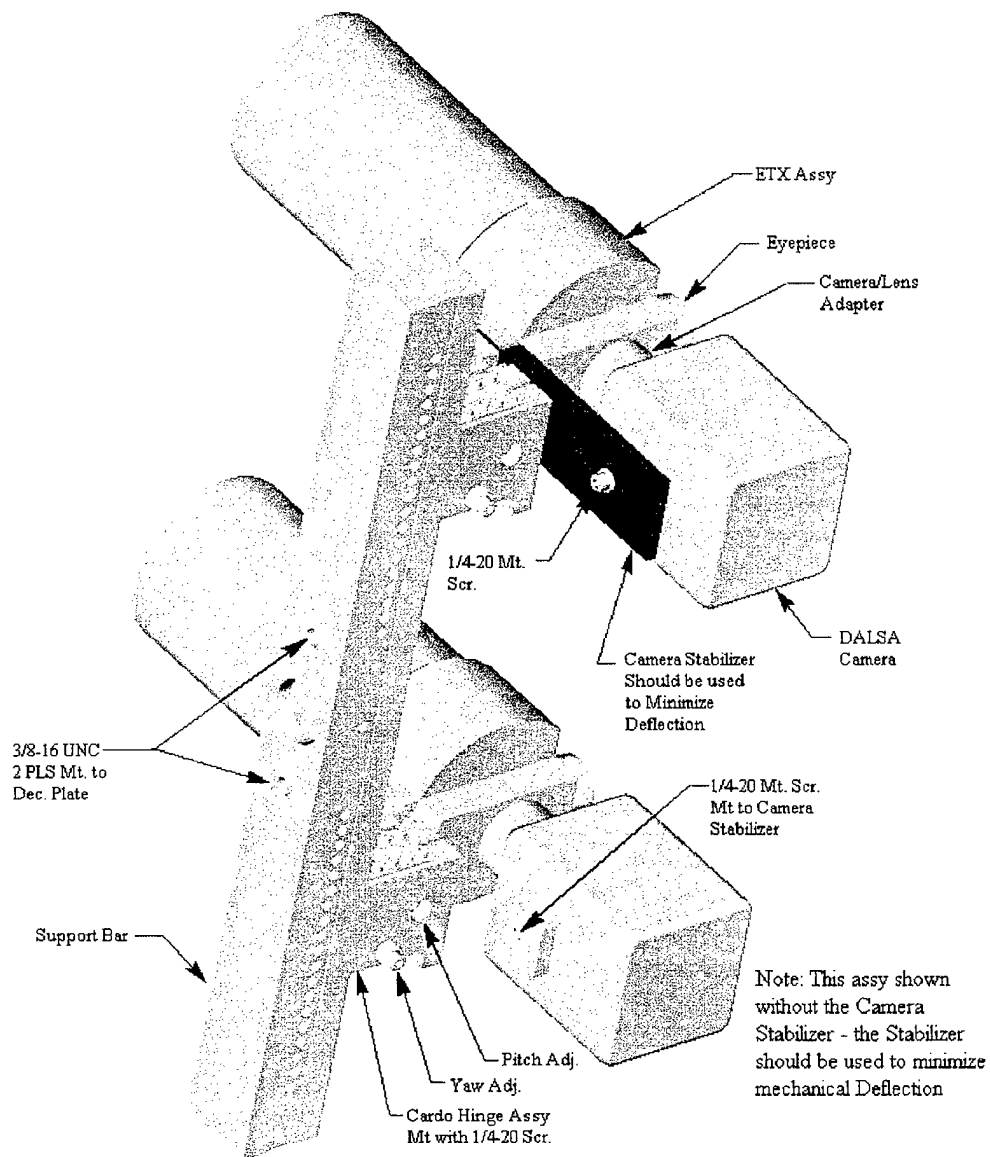
Notes concerning deflections:

- + The Camera Stabilizer greatly reduces deflections and should normally be used to maintain alignment between the camera and the ETX optics.
- + With the Stabilizer in place, a 1.0 in-lb torque in pitch results in about 1 arc minute of angular deflection.
- + Re-centering is quite accurate when the upsetting torque is removed.
- + Electronic cabling to the cameras must be strain relieved to the support bar using the bracket provided. The geometry should be symmetric so that camera angular deflections are similar from camera-to-camera, thus helping to maintain collimation.



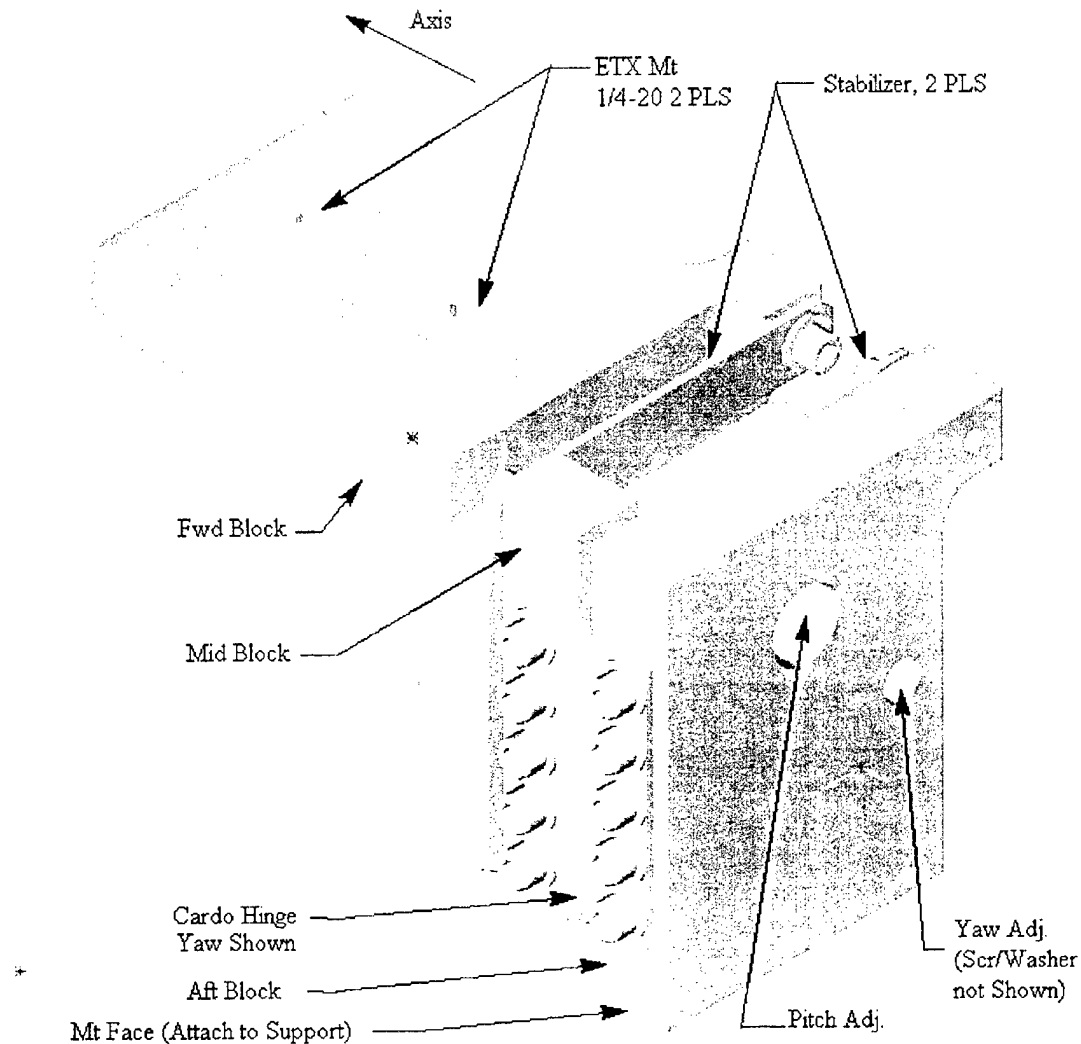
Mount & Optics Assembly – Forward ISO View

The Support Bar mounts two or more optical systems in a 2D configuration. The Cardo Hinge assemblies provide up to $\pm 1.5^\circ$ alignment adjustment each. The collective system bolts to the LXD 750 mount declination axis mounting plate using two 3/8-16 UNF screws. Scope separation is controlled by the $\varnothing 0.257$ mounting holes spaced 10 mm apart. The closest CL-to-CL mounting spacing symmetric about the declination axis is 120 mm.



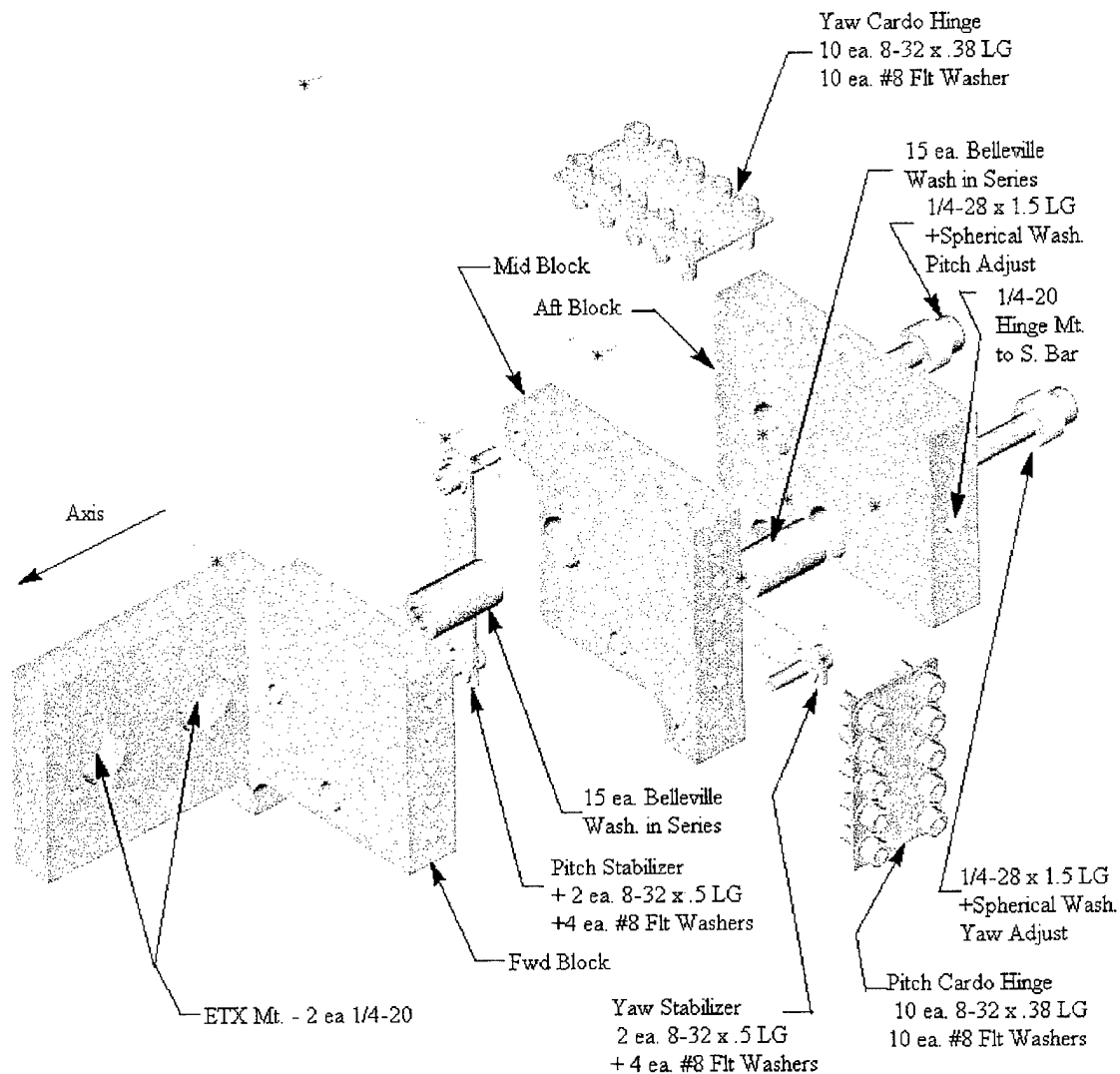
Mount & Optics Assembly – Aft ISO View

Basic Cardo Hinge Detail – ISO View

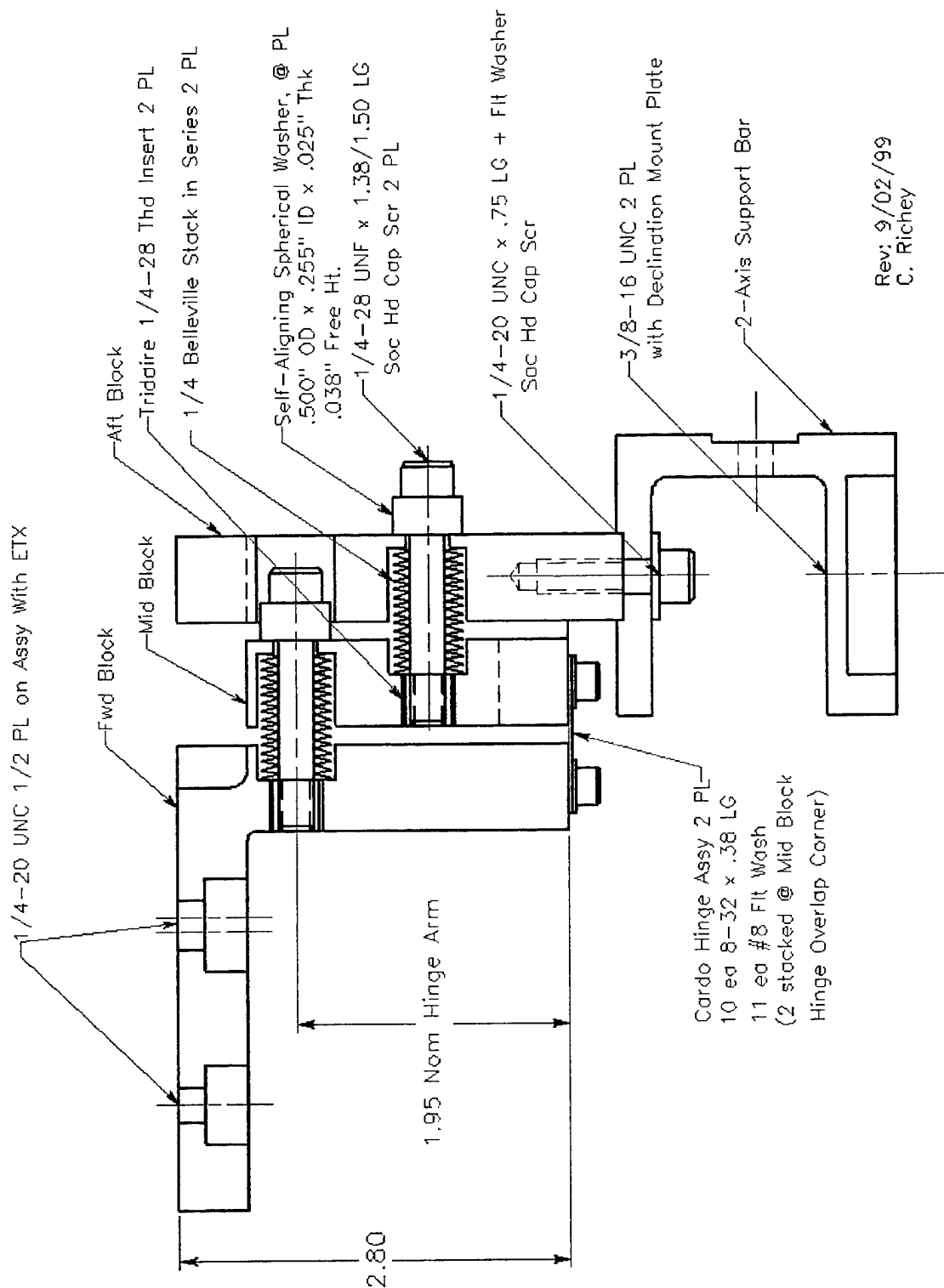


- The Cardo hinges and Stabilizers are made from 300-series stainless steel.
- The hinges are laminated from two sheets to minimize strain.
- The stabilizers prevent "sideways" twisting of the hinge laminate and are thicker with smaller deflections.
- The Belleville washers in series act as a strong spring and hold the Mid Block and Aft Block hard against the 1/4-28 UNF adjustment bolts with a moment of 51 to 196 in-lb (26 washers). A minimum of 26 to a maximum of 36 washers can be used.
- Each turn of the adjustment screw is 1.05°.
- The ETX field of view is 0.101" @ 1250mm, equivalent to 0.118°/ 7.06 arc minutes.
- 1/10th the field of view corresponds to 4.05° rotation of the adjustment, screw equivalent to 0.706 arc minutes.
- Max alignment adjustment is approximately ±1.5° in both pitch and yaw.

Cardo Hinge Assembly - Exploded View



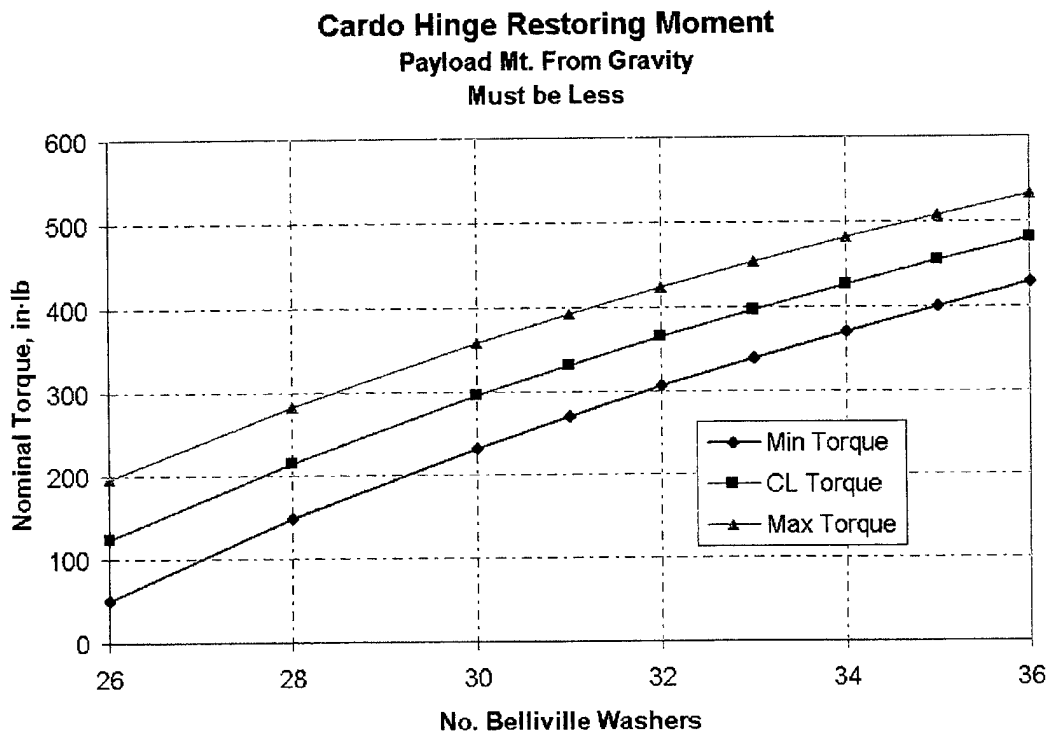
Note: Belleville stacks consist of a minimum of 26 to a maximum of 36 washers – not 15 as indicated in the illustration. Initial supplied quantity is 28. As far as known to the author, the addition of the “stabilizer” is new to this type of system – it provides rigidity at 90° to its hinge axis.



DIMM CARDIO HINGE ASSEMBLY SECTION VIEW

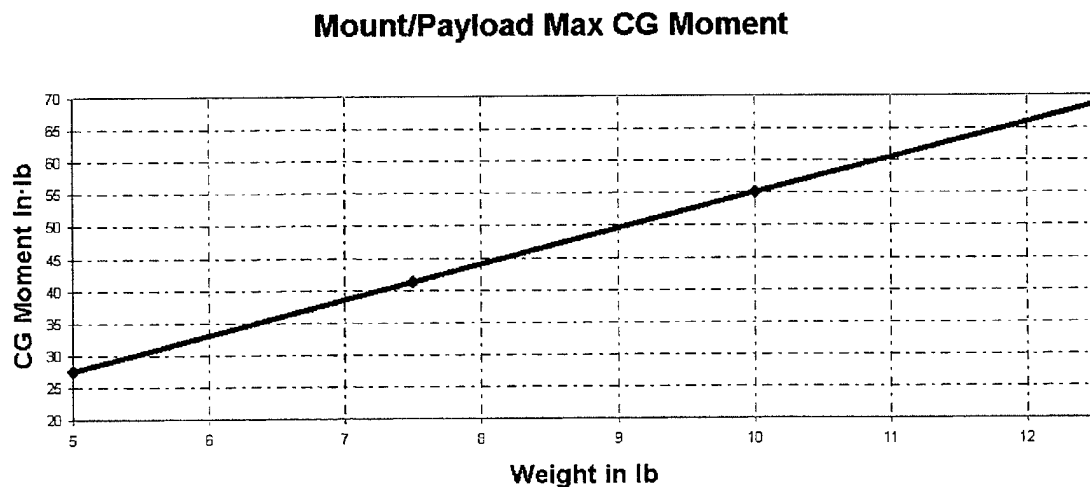
Note that the Belleville washers are in series – the outside diameters and the inside diameters touch alternately (front-to-front & back-to-back).

Cardo Hinge Restoring Moment



Min, CL and Max Torque refer to hinge alignment.

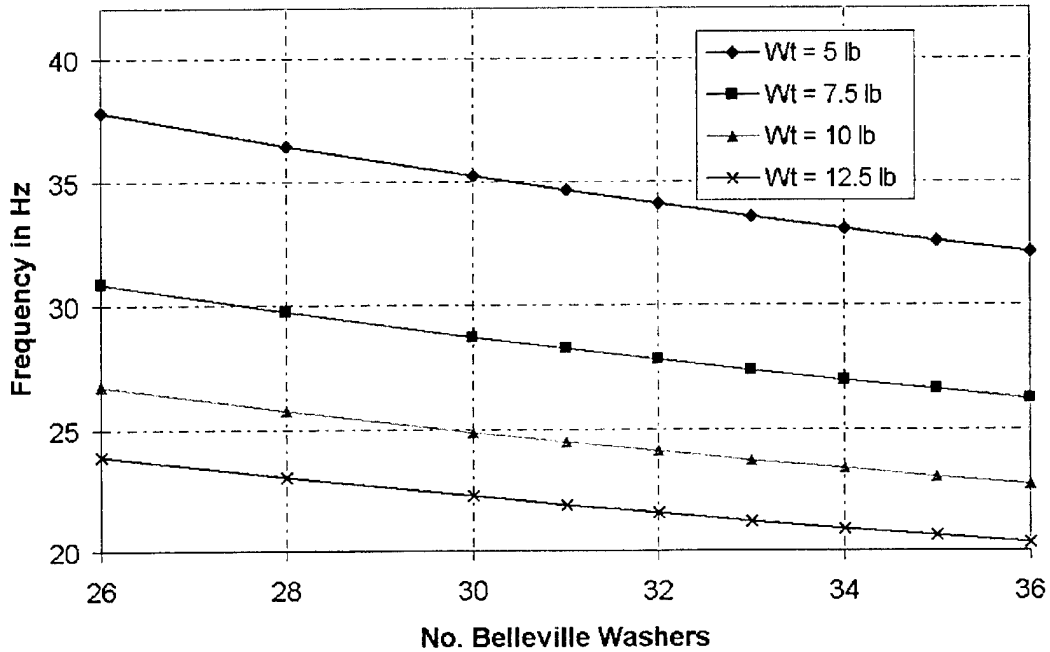
Mount plus Optics Maximum CG Moment



Note: 5.5" CG-to-Pivot arm used. Nominal payload weight is 5-7 pounds.

Modal Frequency of the Cardo Hinge plus Optics Payload

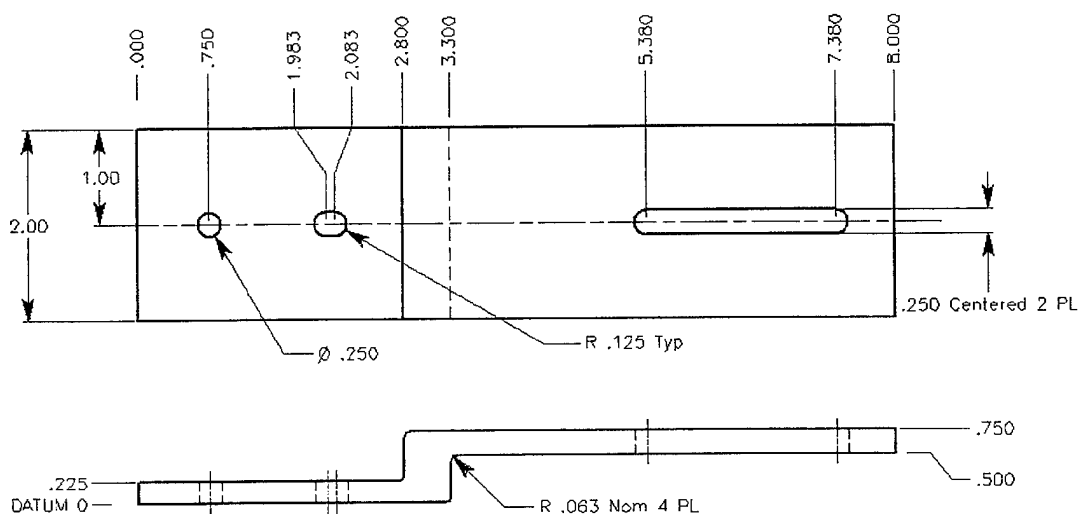
Mount/Payload Min Modal Frequency vs Total Weight
5.5" Max CG Arm Assumed



The Cardo Hinges have very definite resonance points, as they are a spring coupled to a mass. *However, the spring-mass system will not resonate at the spring/mass frequency until "upset" off of the stops* – in this condition extraordinary forces are involved (very heavy winds, someone accidentally leaning against the optics, etc.) and the system is temporarily inoperable. After the forces are removed, the system will return to original alignment (if not damaged) and *act as a rigid body*. Think of the hinges as an engine valve and spring – it is not a coupled spring/mass until unseated and will return to its original alignment at closure.

Parts Drawings

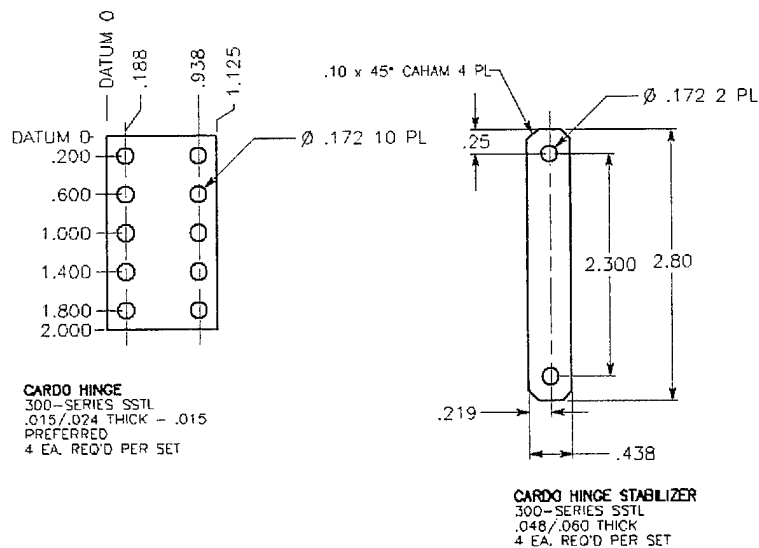
For reference, individual parts drawings are shown.



DIMM 2-AXIS CARDO HINGE CAMERA STABILIZER

1 REQ'D PER SET
MAT'L: 6061-T6/2024-T3 FINISH: ALDINE
SCALE: 1:1
2/14/00 C. Richey

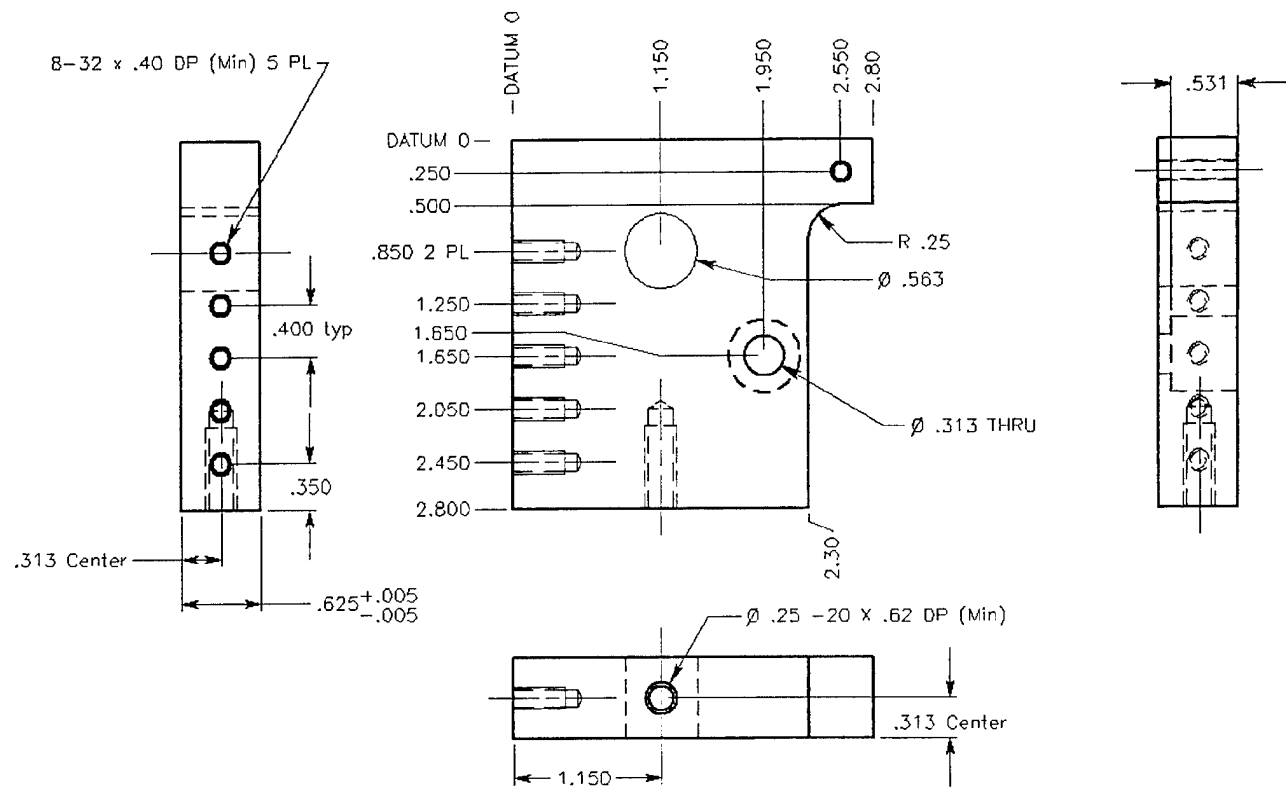
Camera Stabilizer



DIMM 2-AXIS CARDO HINGE SHEET METAL PARTS

NO. REQ'D NOTED
MAT'L: 300-SERIES SSTL FINISH: NONE
SCALE: 1:1
8/24/99 C. Richey

Hinge Sheet Metal Parts



DIMM 2-AXIS CARDO HINGE AFT BLOCK

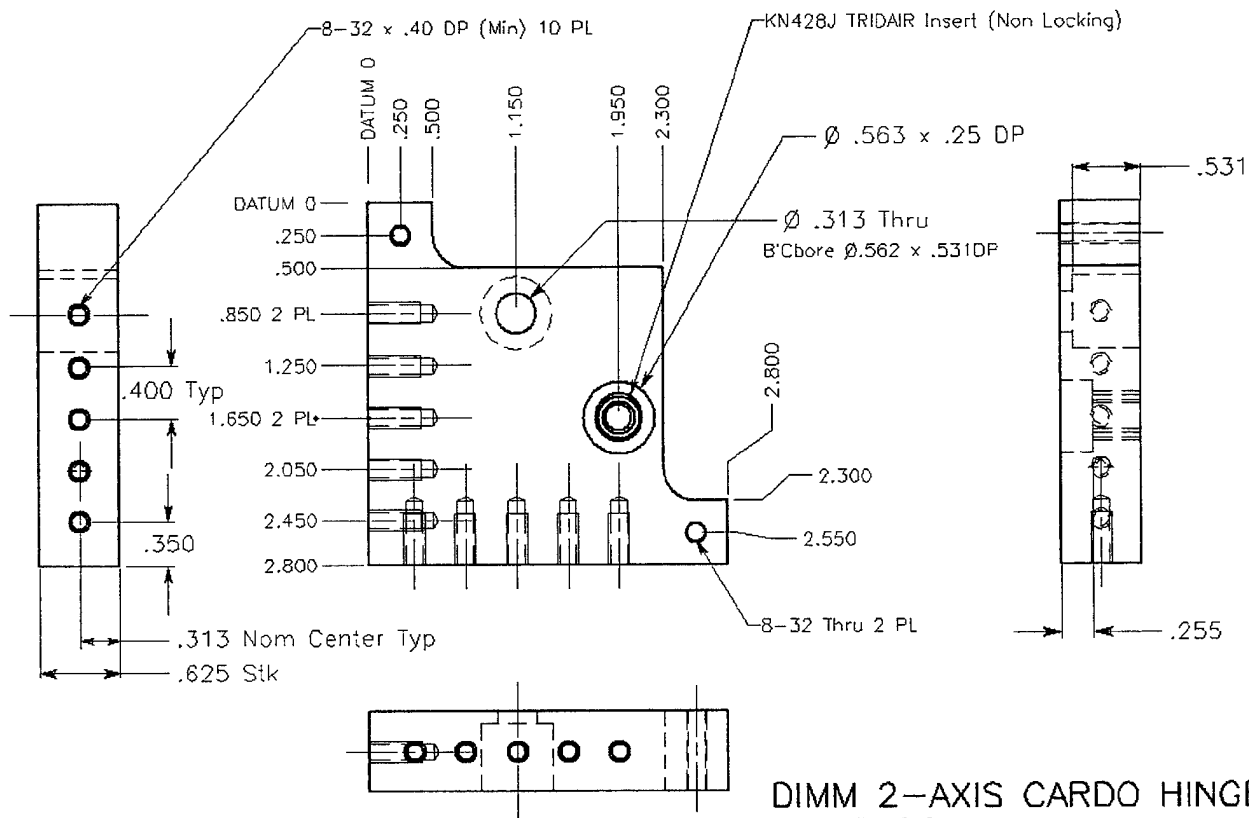
1 REQ'D PER SET

MAT'L: 6061-T6/2024-T3 FINISH: NONE

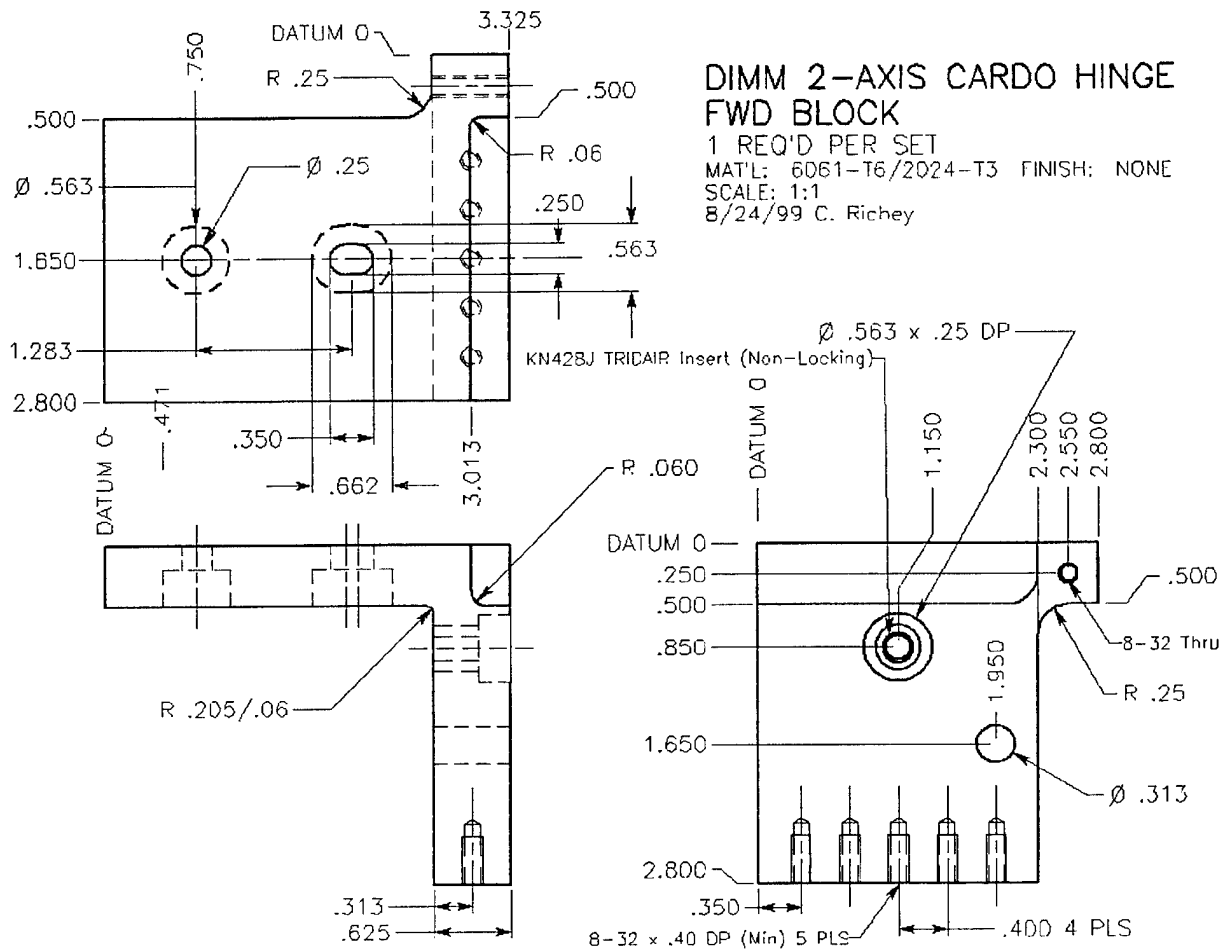
SCALE: 1:1

8/24/99 C. Richey

Aft CARDO Hinge Block

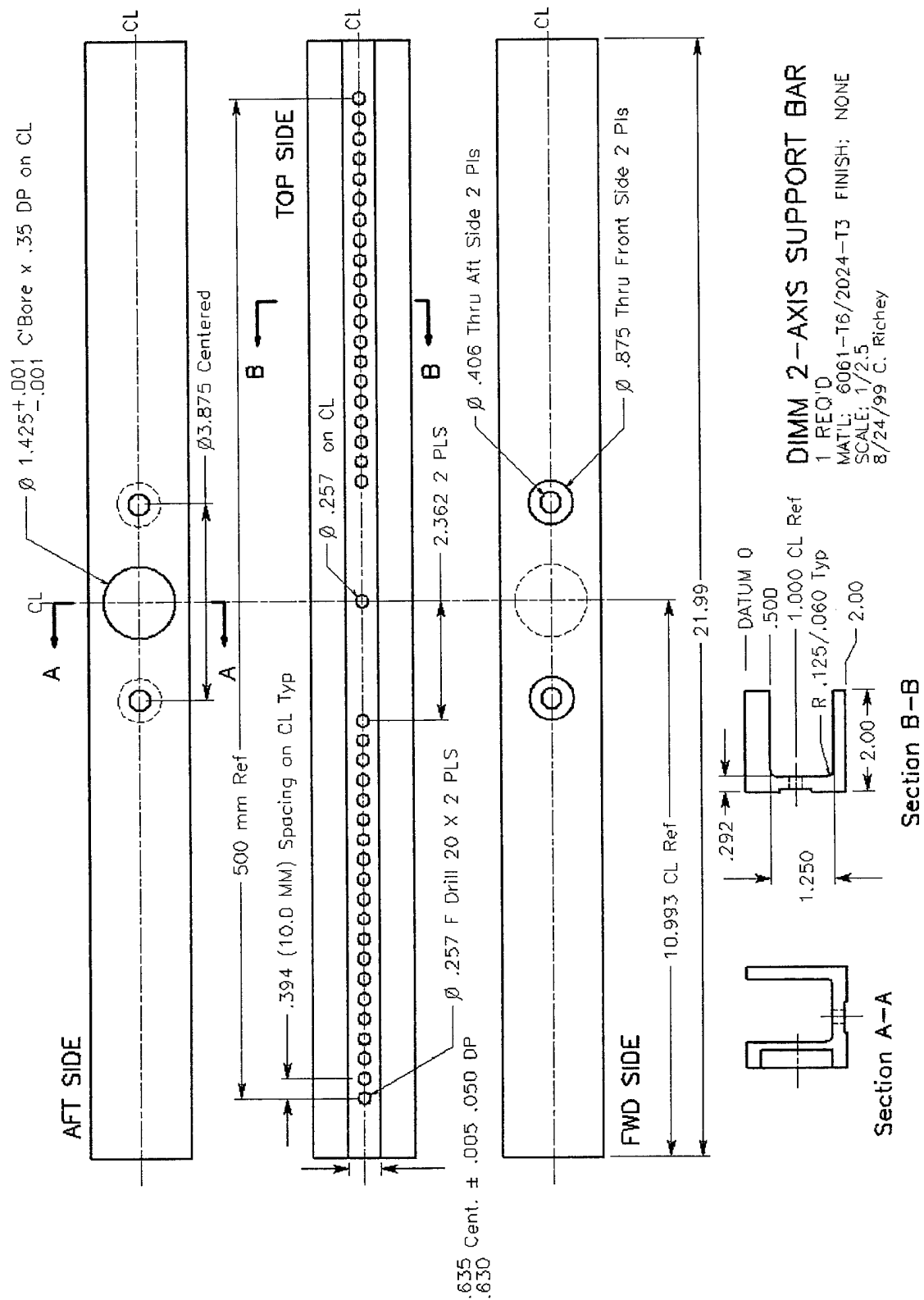


Mid CARDO Hinge Block



Fwd CARDO Hinge Block

Support Bar



DISTRIBUTION LIST

DTIC/OCF

8725 John J. Kingman Rd, Suite 0944
Ft Belvoir, VA 22060-6218

1 cy

AFSAA/SAMI

1570 Air Force Pentagon
Washington, DC 20330-1570

1 cy

AFRL/VSIL

Kirtland AFB, NM 87117-5776

2 cys

AFRL/VSIH

Kirtland AFB, NM 87117-5776

1 cy

Mechanical & Composite Engineering

59775 Spring Creek Road

Montrose, CO 81401

1 cy

Official Record Copy

AFRL/DEBA/Frank D. Eaton

15 cys